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OF DYNAMOS

DIRECT-CURRENT)

s, Engineer-Constructors,
ans-in-charge

BY

VELL, A.M.I.E.E.

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Street, London
of Electrical Engineering"

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Capio Lumen

LONDON
OCKWOOD AND SON
HALL COURT, LUDGATE HILL, E.C.
1907

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THE
CONSTRUCTION OF DYNAMOS

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THE
CONSTRUCTION OF DYNAMOS

(ALTERNATING AND DIRECT-CURRENT)

A Text-Book for Students, Engineer-Constructors,
and Electricians-in-charge

BY

TYSON SEWELL, A.M.I.E.E.

Lecturer and Demonstrator in Electrical Engineering at the Polytechnic,
Regent Street, London
Author of "Elements of Electrical Engineering"

With nearly Two Hundred and Fifty Illustrations and Diagrams
Specially Drawn and Engraved for this Work

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PREFACE

THE present work is an attempt to deal in a single volume of handy size with the Theory, Design, and Construction of Dynamos—both Alternating and Direct-current—in a manner sufficiently detailed to render it of service as a text-book for students and apprentices in electrical engineering, as well as helpful to civil, mechanical, and other engineers who have occasion to deal with electrical matters.

The earlier chapters are accordingly devoted to a brief exposition of the fundamental principles of direct and single-phase alternating currents, and their bearing on the subject of dynamos; the effects of polyphase currents being treated later on, as an introduction to polyphase alternators.

In Electrical construction progress is rapid, and to keep the book within the prescribed limits I have omitted descriptions of machines that are already obsolete, or are rarely met with; the available space being almost exclusively devoted to machines representing present standard practice.

The examples of design given in Chapters IX., XI., and XIV. are there introduced by way of illustration only. The actual designing of dynamos is the work of comparatively few men, most manufacturers having standardized particular lines which, with slight modification, meet most requirements; and in view of the labours of the

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Engineering Standards Committee, further developments in the direction of uniform practice may be expected. Already several excellent works exclusively devoted to this specialized branch of Dynamo design are procurable, while the current issues of Technical journals give information as to the latest details.

I am indebted to Mr. E. C. Roche, A.I.E.E. for his kindness in reading the proof-sheets and preparing several of the illustrations.

TYSON SEWELL.

POLYTECHNIC, REGENT STREET,
LONDON, W.,
February, 1907.

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THE CONSTRUCTION OF DYNAMOS

CHAPTER I

FUNDAMENTAL PRINCIPLES OF DIRECT CURRENTS

THE dynamo is a machine for converting mechanical into electrical energy. It does not generate electricity, for the electricity is already in the copper conductors, as in all other substances, but while the electricity common to all substances is, in the main, without any difference of pressure tending to urge it in any particular direction, the electricity in the conductors of a dynamo, when at work, is under a difference of pressure, so that there is a tendency for a flow of electricity through the conductors. A flow would therefore take place to equalize the pressures, if it were not for the fact that certain substances offer such a resistance to its passage that it is extremely difficult to get the smallest current through them, and that by covering the conductors with such substances we can prevent a flow taking place from one to the other. Such substances are usually spoken of as "insulators," and include, for dynamo purposes, mica, vulcanized fibre, shellac, micanite, presspahn, silk, cotton, etc. Copper forms one of the best conductors, and therefore, where a flow is required, copper is the conductor usually employed, and to prevent the flow taking place in paths not intended, the conductors are covered by one or more of the insulating materials, usually shellaced cotton.

It will be seen that the dynamo, whatever its size or form, is simply an electrical pump, and does for electricity and electrical engineering what a pump does for water and hydraulic engineering, viz. creates and maintains a difference of pressure against the tendency of the current to equalize the pressure.

The current that flows depends, in every case, on the pressure difference maintained by the dynamo and the resistance of the circuit, such that—

$$\text{current} = \frac{\text{difference of pressure}}{\text{resistance}}$$

From this it follows that the difference in pressure required to get any given current through any given resistance is equal to the value of the current multiplied by the resistance. In electrical work this is known as Ohm's Law, and is of the greatest assistance throughout.

The pressure difference created by the dynamo does not depend on its size. We can get exceedingly high pressures from very small machines, but pressure difference is not the only thing required. The actual requirement, in most cases, is to produce a certain current through circuits of certain resistance, and therefore a certain pressure difference is essential. But the current in passing through the circuit has also to pass through the dynamo, just as the water has to pass through the hydraulic pump when at work in hydraulic systems, and to get the current through the dynamo we require a certain minimum size for the conductors, for the current they will carry depends on, and is proportional to, their size or sectional area. The current in passing through any conductor produces heat in it in proportion to the product of the square of the current and the resistance of the conductor. In the dynamo, therefore, we have to consider two things—the pressure difference generated by it, and the maximum current it will carry. These two factors determine the *power* the dynamo is able to exert, for the power, or rate of doing work, depends on both pressure and current.

The current is the rate of flow in every case, thus ten gallons per second is a definite current of water, and in the same way ten *coulombs* per second is a definite current of electricity, the coulomb being the practical unit *quantity* of electricity. This would be spoken of as a current of ten *amperes*. Electrical pressures are measured in *volts*, while electrical power is measured in *watts*. If a rate of flow of one coulomb per second—*i.e.* one ampere—be maintained under a pressure of one volt, the power (rate of doing work) is one volt-coulomb per second, or one watt.

For scientific purposes, the units of quantity and current are ten times larger than the coulomb and the ampere, while the unit

[redacted]

of electrical pressure is 100,000,000 times smaller than the volt. These units are known as "absolute" units, the practical units being multiples of them.

Electricity can be put under a difference of pressure in several ways. In the case of the dynamo, it is done by making the copper conductors cut through a strong magnetic field, and the electrical pressure difference produced in this way is proportional to the *rate* of cutting, as we shall see later.

The magnetic field is, for convenience, supposed to be made up of a number of magnetic lines stretching from pole to pole, through the iron or steel, and across the air space, each line thus forming a closed magnetic circuit. These lines of force are only imaginary. The *whole* of the space in which a magnetic field exists is in a state of stress, the same at all parts, though often varying in degree or intensity, *not* (as might be supposed from the expression "lines of force") in a series of lines with spaces between, free from magnetic influence. Soft iron and mild steel offer an easy path for these lines, while air, brass, copper, zinc, gun-metal, and most other materials offer a relatively difficult path. For this reason, where strong magnetic fields are required, the circuit is built up of iron or steel as far as possible. The dynamo may therefore be considered as practically a copper-iron machine, both electrical and magnetic considerations coming into the design to nearly equal degree.

We have already stated that when a conductor cuts through magnetic lines of force an electrical pressure difference is established in the conductor proportional to the rate of cutting. If there be a complete conducting circuit, a current will flow in it, depending on the pressure difference and the resistance of the whole of the circuit. There is, therefore, some relation between magnetism and electricity, such that if we have a magnetic field we can get electric currents; and the converse is also true, for the current flowing round the circuit gives rise to magnetism, and it is only necessary to arrange the circuit appropriately to make the magnetic field produced almost as strong as we please.

The *rate* of cutting magnetic lines of force by conductors, which determines the electrical pressure difference generated, or the *electromotive force*, as it is called, will obviously depend on, and be proportional to, (1) the number of magnetic lines cut in a given time; (2) the number of conductors in series, cutting

[redacted]

the magnetic lines; (3) the inverse time taken in the cutting, or—

$$\text{rate of cutting lines of force} = \frac{N \times C}{t}$$

where N = total lines of force cut;
C = total number of conductors employed in cutting;
t = time in seconds or fractions of a second taken in the operation.

The electromotive force, for practical purposes, is measured in volts. The above expression for the rate of cutting magnetic lines of force does not, however, give the electromotive force in volts, but in absolute units. These units are 100,000,000 times smaller, and too small for practical purposes. We convert them into volts, therefore, by dividing by 100,000,000 or 10^8, so that—

$$\text{E.M.F in volts} = \frac{N \times C}{10^8 \times t}$$

The formula for the electromotive force generated by a dynamo has to be modified somewhat, owing to the fact that in all dynamos the cutting is performed by a rotation of the conductors.

From what has been said, it will be understood that the dynamo can develop its electromotive force without delivering a current to the circuit, for if the circuit be broken (switched off) at any part, it will be impossible for a current to flow in it, whereas this will not interfere with the electromotive force, which will tend now, as before, to urge a current round the circuit. In this case, however, the dynamo is delivering no power, and is also absorbing very little, only sufficient to overcome its own internal losses. As soon as a current flows, the dynamo begins to deliver power to the circuit equal to the product of amperes and volts. Thus, suppose in a given case the dynamo delivers 100 amperes under a pressure of 500 volts, then it is delivering power to the circuit equal to 100 × 500 = 50,000 watts.

One horse-power being equivalent to 746 watts, in this case it would be supplying energy to the circuit at the rate of $\frac{50000}{746} = 67$ h.p.

This amount of energy will be absorbed at different parts of the circuit in proportion to the resistances to be overcome at the various parts. Ohm's law tells us that the total resistance of the circuit will be equal to the electromotive force divided by the current; therefore in the above case, total resistance $= \frac{500}{100} = 5$ ohms (*ohm* being the name given to the unit of resistance). Suppose these 5 ohms to be made up of different small portions, say 0·5, 1, 1·5, and 2 ohms, as in Fig. 1. The 100 amps. will flow through them all in series, but the power absorbed at the various points will be equal to the value of the current, multiplied by the electromotive force by which the current is urged through them.

Now, according to Ohm's law, the electromotive force required to get any current through any resistance will be equal to the product of the current and the resistance, so that here the electromotive force required to get 100 amperes through the resistance of 0·5 ohm will be $100 \times 0{\cdot}5 = 50$ volts, while that necessary to get the same current through the remaining resistances will be $100 \times 1 = 100$ volts, $100 \times 1{\cdot}5 = 150$ volts, and $100 \times 2 = 200$ volts respectively, showing us that the electromotive force in the circuit divides itself in proportion to the resistances to be overcome. The power absorbed at each part is therefore proportional to the resistance, thus the power absorbed on the 0·5 ohm resistance is equal to $100 \times 50 = 5000$ watts, while on the other resistances we have $100 \times 100 = 10{,}000$ watts, $100 \times 150 = 15{,}000$ watts, and $100 \times 200 = 20{,}000$ watts.

The power absorbed by the different resistances is transformed into heat; the heat being exactly in proportion to the power absorbed at the different parts. This being equal to EC, is also equal to C^2R, for according to Ohm's law, $E = C \times R$, and therefore $E \times C = C \times R \times C = C^2R$. The heat developed in any resistance is therefore proportional to the value of the resistance, and to the square of the current it is carrying.

But it has been pointed out that the current flowing round the circuit, being but a circulation, must also flow through the dynamo conductors, and some electromotive force will therefore be required to get the current through them, and some power absorbed in them, depending on their resistance; thus, suppose the resistance of the dynamo conductors be 0·025 ohm, then $100 \times 0{\cdot}025 = 2{\cdot}5$ volts will be required, and $100 \times 2{\cdot}5 = 250$ watts will be absorbed in the dynamo itself, irrespective of that required for the circuit outside the dynamo. It will therefore be seen that if we want 50,000 watts at 500 volts for the circuit apart from the dynamo, we must generate in the above case 50,250 watts at 502·5 volts, to allow for the loss in the machine. The 502·5 volts would be spoken of as the "electromotive force" generated, while the 500 volts would be called the "potential difference" on the dynamo terminals at full load. We shall see later that there are other things tending to reduce the potential difference when the machine delivers a current.

The conductors arranged as in Fig. 1 are said to be in *series*. In this case there is only one path for the current, which must therefore have the same strength at all parts, but in many cases of dynamo circuits the current has more than one path, in which case the conductors are said to be in *parallel*. In all parallel circuits the current divides in inverse proportion to the various resistances, and flows under the same electromotive force in each. The combined resistance of a number of conductors in parallel is always less than that of the smallest among them, for the addition of resistances in parallel, by opening up additional paths for the current, is reducing the total resistance of the circuit, whereas in series, every additional resistance adds to the total resistance.

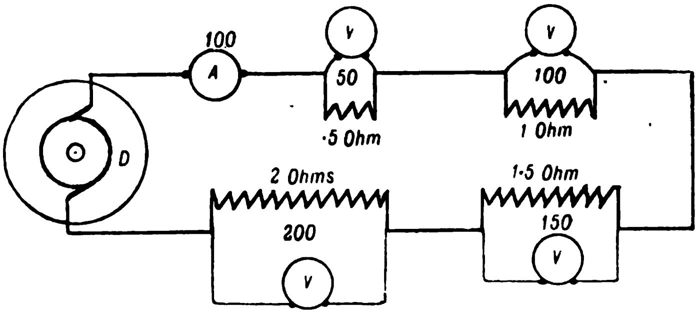

FIG. 1.

The resistance of any number of similar resistances in parallel is always equal to that of one divided by the number, and conversely, the resistance of any one of a number of similar resistances in parallel is equal to the resistance of the combination multiplied by the number. When the resistances are not similar—a case

[redacted]

seldom or never met with in dynamo circuits—the resistance of any number in parallel, say r_1, r_2, r_3, etc., is equal to—

$$R = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} +}$$

thus, three resistances of 0·5 ohm, 1·5 ohms, and 3 ohms, in parallel will have a combined resistance of—

$$R = \frac{1}{\frac{1}{0·5} + \frac{1}{1·5} + \frac{1}{3}} = \frac{1}{\frac{6 + 2 + 1}{3}} = \frac{1}{\frac{9}{3}} = \frac{3}{9} = 0·33 \text{ ohm.}$$

The resistance of any conductor is proportional to (1) its length, (2) inversely to its sectional area, and (3) to the specific resistance of the material. If we take unit length and sectional area of various substances, the resistances are known as "specific resistances;" the only variation being in the nature of the materials. The resistance of any conductor can therefore be expressed in the form of an equation, thus—

$$R = \frac{\text{length}}{\text{sectional area}} \times \text{specific resistance.}$$

The specific resistance of copper—which is practically the only conductor employed in dynamo windings—is 0·0000018 ohm at the ordinary temperature of 15° C. That is to say, the resistance of a cube of copper of 1 cm. side, measured from face to face, has the above value. If, therefore, the length be 100 cms., the resistance will be 100 times greater, while if the sectional area be $\frac{1}{100}$ sq. cm., 100 times greater still. It will be seen that, knowing the value of the specific resistance, we can calculate the resistance of any wire by noting its length and sectional area. As the dimensions are often more easily measured in inches and square inches, the specific resistance is often more conveniently given as the resistance of one-*inch* cube. This value is 0·00000066, or $\frac{0·66}{10^6}$ ohm, at 15° C.

As an example, let us take a field-magnet coil for a dynamo, having, say, 1500 turns, mean length of one turn 50 inches, sectional area of the wire 0·008 square inch. What will be its resistance?

[redacted]

$$R = \frac{\text{length}}{\text{sectional area}} \times \text{specific resistance}$$

$$\text{therefore } R = \frac{1500 \times 50}{0{\cdot}008} \times \frac{0{\cdot}66}{10^6} = 6{\cdot}2 \text{ ohms.}$$

The electromotive force or pressure, and the current, are in practical work usually read direct on instruments known as "voltmeters" and "ammeters." The ammeter is put into the main circuit, so that the whole current delivered passes through it, while the voltmeter is connected across the terminals of the dynamo, or any other part of the circuit, where it is desired to know the pressure difference (see Fig. 1). Instruments known as "wattmeters" are also used at times for indicating the power in watts, while insulation resistances are sometimes indicated on "ohmmeters."

Resistances of medium value are measured in several ways. A field coil similar to that considered above could most readily be measured by means of the Wheatstone bridge. This consists of sets of resistances arranged, together with the one under test, in two parallel circuits as shown in Fig. 2. A battery (connected to *a* and *d*) sends a current along both circuits under the same potential difference. There is, therefore, a potential difference on the ends of *ab* and *bd*, the ratio between them being also the ratio of the resistances *ab* and *bd*. In the same way we have potential differences on *ac* and on *x* proportional to their resistances. If now the ratio between *ab* and *ac* be known, and *bd* be an adjustable resistance of known value, we can so adjust *bd* that the ratio of the potential differences on *bd* and on *x* is the same as that on *ab* and *ac*.

When this is the case, there will be no *difference* in potential between the points *b* and *c*, and therefore a galvanometer, when connected across these points, will show no deflection. The ratio of the potential differences on *ab* and *ac* is then the same as the ratio of their resistances, and this is also the ratio of the resistances *bd* and *x*; and knowing *bd*, we get *x* by simple proportion, or—

$$ab : ac :: bd : x$$

$$\text{therefore } x = \frac{ac \times bd}{ab}$$

For very small resistances, such as that of a dynamo armature, a fall of potential method is most suitable. In this the armature is connected in series with a standard resistance of low value, say, 0·01 ohm. A current is then sent through them, and, being in series, the current will have the same value in the two at the same time. Now, by Ohm's law the potential on each will be proportional to their resistances, for $E = C \times R$ in each case. The readings of a millivoltmeter applied to the ends of the two, taken separately, will give the ratio of the resistances, and, knowing one, we find the other by simple proportion. Thus, suppose the reading on the dynamo armature be 10, while on the standard resistance it is 15 millivolts, then—

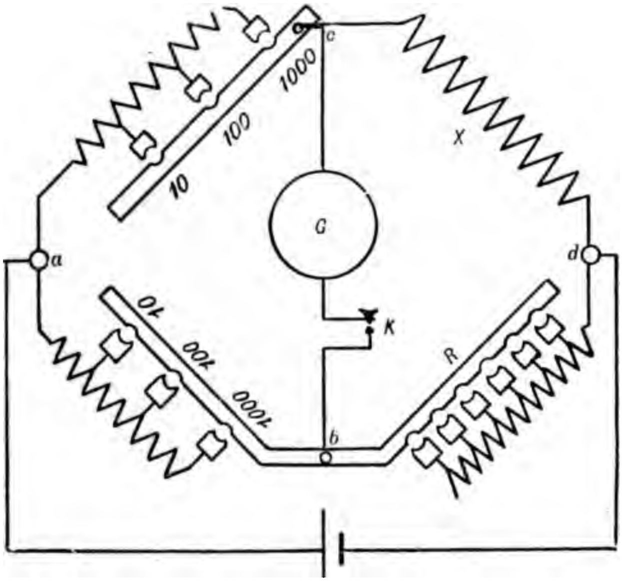

FIG. 2.

$$10 : 15 :: x : 0{\cdot}01$$

$$\therefore x = \frac{10 \times 0{\cdot}01}{15} = 0{\cdot}00\dot{6} \text{ ohm}$$

A diagram of the connection for this measurement is given in Fig. 3.

The resistance offered by the insulating materials employed in dynamo construction is usually exceedingly high, and therefore

[redacted]

measured in "megohm" (million ohm) units. In working, the insulation often gets heated, and this reduces its resistance considerably; consequently, it is advisable to measure the insulation resistance when heated to the maximum that will ever occur in its normal working. It is also important that the pressure at which the measurement is made should be at least equal to that which the insulation has to withstand, and it is better still to employ a pressure two or three times greater. The insulation resistance of many substances falls considerably when subjected to a high pressure, and may therefore show a high value when tested with a few cells, and yet give a low value when subjected to the normal working pressure. The most direct method of measuring insulation resistance, and the one most commonly employed, is by means of a testing set such as the "Silvertown" set, or by Evershed's "megger."

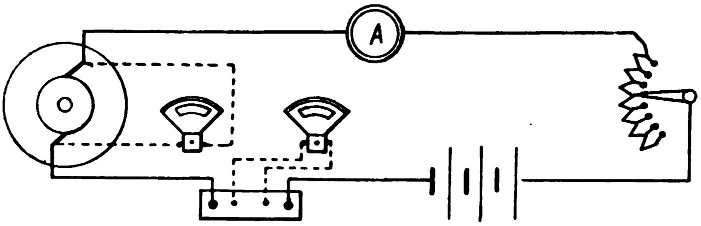

FIG. 3.

With the latter, the scale is calibrated in megohms, and the value of the insulation resistance can be read direct without any calculations whatsoever (see Fig. 4). A small magneto, or permanent magnet hand dynamo, capable of generating an electrical pressure up to any desired value, is contained in a box, together with the instrument, and the pressure is applied by simply turning the handle. With a generator of 500 volts pressure, the range is from 0 to 100 megohms, while with a 1000-volt generator the range extends to 200 megohms, and higher ranges can be obtained, even up to 4000 megohms if required. In measuring the insulation resistance of a field coil, for instance—after the machine has been running for a few hours, so that the final temperature has been reached, the end of the winding is connected to one terminal of the instrument, the other terminal being connected to the coil frame, if of metal, or to the machine frame. Any current that then flows must do so through the insulating material. The handle is now turned, gently at first, to see that all is right, and the winding then disconnected from the instrument for a moment to check the zero, for with no connection to the instrument the needle should point to infinity. After connecting up again, the handle is turned at anything over 100 revolutions per minute, and the insulation resistance is then read from the indication of the pointer on the scale.

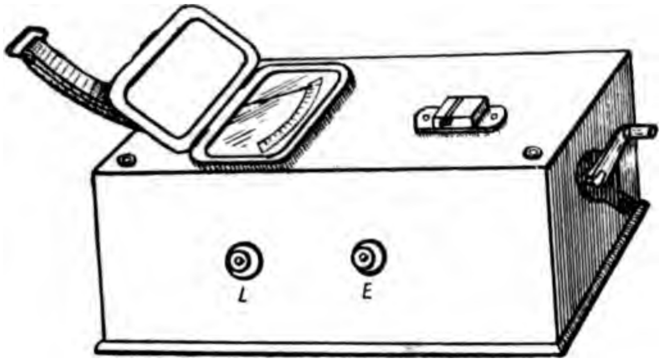

FIG. 4.

With such instruments as the Silvertown testing set, a little calculation is required with each measurement. In this case a sensitive galvanometer, with scale readings proportional to the current, and with shunts for reducing its sensitiveness, is enclosed in a box together with a resistance coil of 50,000 ohms, which may be connected in the galvanometer circuit by means of a plug switch. Two terminals at the top are provided for connecting to the insulation resistance, and this, or the 50,000 ohm coil, may be interchanged by means of the plug switch. A second pair of terminals to the side of the instrument are to be connected to a portable battery of dry cells, giving the required electromotive force (Fig. 5).

To use the instrument, the 50,000 ohm coil is first plugged into the circuit, the galvanometer shunted to reduce its sensitiveness to the minimum, and the battery then connected up. If the needle gives but a small deflection, the 50,000 ohm coil should

[redacted]

be first unplugged and the second shunt inserted instead of the first. The 50,000 ohm coil is then plugged in again, and the reading on the scale noted. The 50,000 ohm coil is next disconnected, and the insulation resistance substituted by inserting the plug in the second hole marked "insulation," the shunts being again adjusted as before till a suitable reading is obtained. A very short calculation then gives the value of the insulation resistance.

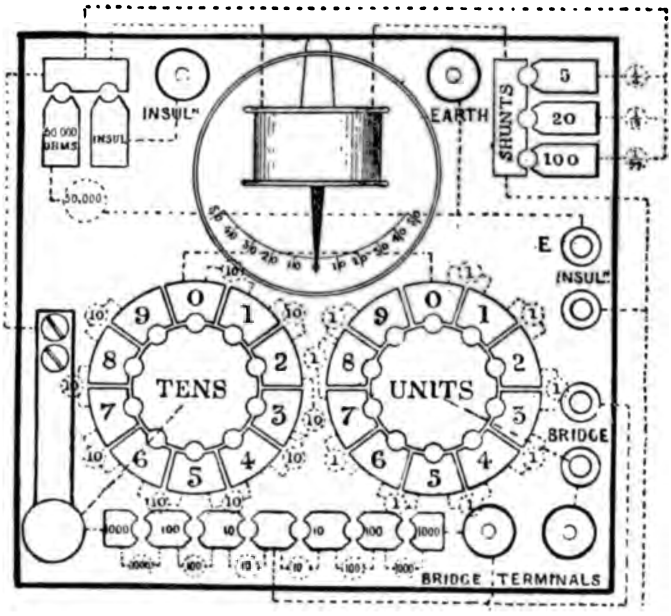

FIG. 5.

As an example, suppose with the $\frac{1}{20}$ shunt and the 50,000 ohms we obtain a deflection of 35 divisions, while with the insulation resistance and no shunt we obtain a deflection of 10 divisions, then with the 50,000 ohm coil with no shunt we should have obtained a deflection of $35 \times 20 = 700$ divisions. The currents in the two experiments were therefore in the proportion of 700 : 10, or 70 : 1, and with the same electromotive force, the currents are inversely proportional to the resistances (Ohm's law).

[redacted]

Therefore $50{,}000 : x :: 1 : 70$
therefore $x = 50{,}000 \times 70 = 3{\cdot}5$ megohms.

The remaining connections at the lower part of Fig. 5 are arranged as a form of Wheatstone bridge, and are intended for testing conductor resistances.

If we consider *similar* lengths of copper, varying in sectional area and in the current carried, we see that, owing to the lengths and specific resistances being the same for all, the resistances are proportional to $\frac{1}{\text{sect. area}}$. The voltage drop, being proportional to $C \times R$, is therefore proportional to $C \times \frac{1}{\text{sect. area}}$, or to $\frac{\text{current}}{\text{sect. area}}$, *i.e.* to the current carried per unit of sectional area. This ratio is known as the *current density*. We speak of a current density of, say, 1000 amps. per square inch, which tells us nothing of either the current or the sectional area; but we know that if the sectional area be 0·1 sq. inch, the current is 100 amps., and if 0·01 sq. inch, the current is 10 amps., and so on, and the voltage drop will be the same for similar lengths whatever the current or sectional area may be, providing the current density is the same for all.

The power absorbed by the same length conductors, if of the same material, varies with the square of the current density. Thus, suppose we wish to deliver 50 amps. through a conductor $\frac{1}{40}$ sq. inch in sectional area, the current density will be 2000 amps. per square inch, and the power absorbed per unit of length will be proportional to C^2R, therefore proportional to $50^2 \times \frac{1}{\text{sect. area}}$. If now we double the current through this same conductor, the power absorbed will be proportional to $100^2 \times \frac{1}{\text{sect. area}}$, or, the current density being doubled, the power absorbed by the conductor is quadrupled, assuming the specific resistance to remain unaltered.

In the above case, however, the amount of heat developed in the circuit being much greater in the second than in the first case, the specific resistance will *not* remain unaltered. With copper, the specific resistance varies by 0·428 per cent. for every degree

[redacted]

difference in temperature, and the quantity of heat would have been four times greater in the second case than in the first had the resistance remained unaltered; but with the increase in temperature we get also an increase in resistance. Suppose the resistance in the first case to be, say, 2 ohms, and the rise in temperature 60° C., then the resistance in the second case will be equal to—

$$\begin{aligned} R_2 &= 2 + (0{\cdot}428 \text{ per cent. of } 2 \times 60) \\ &= 2 + (0{\cdot}00428 \times 2 \times 60) = 2{\cdot}5 \text{ ohms} \end{aligned}$$

an increase of 25 per cent. This is usually put into the general formula—

$$R_2 = R_1(1 + aT)$$

where a is the temperature coefficient of the material, and T the temperature rise in degrees Centigrade.

The specific resistance and temperature coefficient of copper are very important factors in the design of the dynamo, where this metal exclusively is used as a conductor. In the accompanying regulating apparatus such as rheostats, however, various metals and alloys are used, having very different values for these properties. The following table gives the values of specific resistance and temperature coefficient for a number of metals :—

Metal.	Specific resistance, ohms per cm. cube at 0° C.	Specific resistance, ohms per inch cube at 0° C.	Temperature coefficient, per cent. increase per degree C.
Copper, pure (annealed)	0·00000169	0·000000625	0·428
Phosphor-bronze . . .	0·0000036	0·00000141	0·394
Brass	0·00000630	0·00000248	0·158
Iron, pure (wrought) .	0·00000907	0·00000357	0·625
Nickel	0·0000123	0·00000485	0·620
Nickel steel	0·0000295	0·0000116	0·201
German silver	0·0000300	0·0000118	0·036
Platinoid	0·0000417	0·0000164	0·031

It should be noticed that in all the alloys the values vary somewhat, depending on slight differences in the percentage composition. Those given in the table may be taken as good average values. A very small amount of impurity in those

[redacted]

marked "pure" will, however, increase the specific resistance very considerably. Take iron, for instance, the specific resistance pure is 0·00000357 ohm per inch cube; but ordinary commercial wrought iron, annealed, has the value 0·00000544, an increase of over 50 per cent.

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CHAPTER II

THE MAGNETIC FIELD

WHEN an electric current flows through any conductor, a magnetic field, circular in shape, springs from the centre of the conductor into the surrounding space, jacketing it, as it were, for its entire length. This might be compared with the heat surrounding a steam-pipe when carrying a current of steam, and, as the heat falls off as we recede from the steam-pipe, so does the magnetic field fall off in intensity as we go farther from the conductor (see Fig. 6).

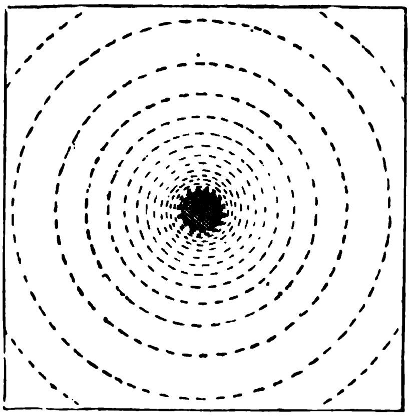

FIG. 6.

This magnetic field can penetrate all known substances in about equal degree, with the exception of iron, steel, and nickel, which are much easier of penetration; for instance, if a thick tube of wood or brass be placed round the conductor, the magnetic field is not altered, for the brass or wood are penetrated just as easily as the air which they have displaced. With a thick tube of iron, however, the field in it would be much more intense.

The iron need not necessarily surround the conductor, for if placed anywhere in the field, the lines of force will be distorted, and pass into and through the iron in greater numbers than in the air-space. The iron will then exhibit all the properties of a magnet, and is said to be magnetized by induction. The stronger the field in which the iron is placed, the stronger will be the induced field in the iron. The iron being more easily penetrated by magnetic lines, *i.e.* offering less magnetic resistance than the air, the actual number produced will be greater owing to its proximity; and when the iron is put into that part of the magnetic circuit where the resistance is highest, the increase in the number of lines of force produced is often very great.

The lines of force, or "flux," as it is often called, forming a magnetic field, exerts a force in a particular direction on magnetic materials (iron, steel, etc.), on magnets, and on other current-carrying conductors. For convenience, the direction of the field is spoken of as the direction in which a north pole would be moved if placed in the field, *i.e.* from north to south. There are various rules for finding the direction of the field without actually testing with a north pole. Perhaps the best of these is that known as the screw rule. If a current be flowing in any conductor, a north pole will be urged round it in the direction in which an ordinary screw has to be turned to move it in the direction of flow of the current.

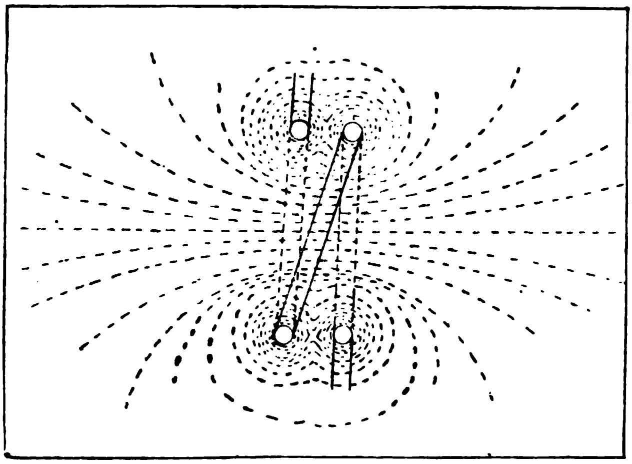

FIG. 7.

The shape of the magnetic field can be altered by bending the conductor carrying the current; thus, if the conductor be bent into a circle, the magnetic field produced will have the shape shown in Fig. 7, and by twisting it into a spiral or long coil, we get the field changed from circular to straight in the space enclosed by the conductors, as shown in Fig. 8. This arises from the fact that the magnetic lines created by one loop of the wire link themselves on to those created by the next to it; the fields are said to be attractive, and all the separate fields created by the various loops of wire combine to give one resultant field round the whole. It will be noticed that the magnetic field, in any and every case, completes a magnetic circuit; that is to say, if we start at any point in the field, we can always trace it round in paths, some long and some short, to return to the starting-point. The current also has to complete a circuit, and in doing so creates a magnetic field whose circuit is interlinked with it.

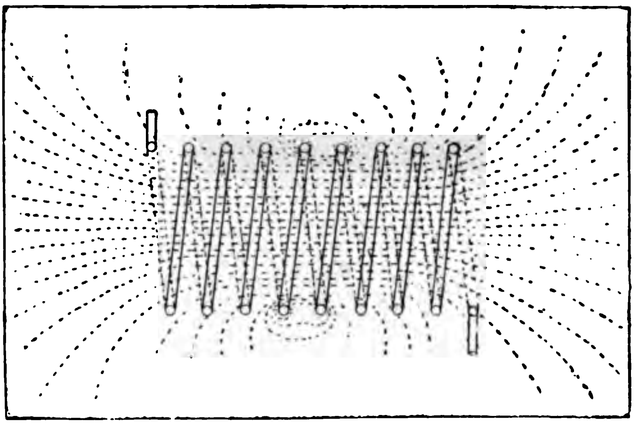

FIG. 8.

The lines of force so created are self-repellent; that is, each line of force is repelling every similar line, so that they tend to spread apart. The current in the coil represents the energy required to squeeze the lines together inside the coil. Outside they spread out to such an extent that practically no force is required for that part of the magnetic circuit.

The field created in this way has a definite direction, which can be reversed by simply reversing the current in the conductors, or, leaving the direction of the current unaltered, by winding the conductor in the opposite direction. If the right hand be outstretched with the palm on the conductors, and the fingers point ing in the direction of the current, the thumb, which normally stands at right angles to the fingers, will point in the direction of the north pole.

It has been explained that the magnetic field is, for convenience, supposed to be made up of lines of force. This enables us to speak of the strength or intensity of various magnetic fields as containing so many lines of force to the square inch or square centimetre. With any given number of lines of force, the field can be more or less intense, depending on the sectional area through which they pass; thus, with a field of 1000 lines of force, the intensity will be unity if they all pass through a sectional area of 1000 sq. cms., but if the same number of lines pass through 1 sq. cm. of sectional area, the *intensity* will be 1000 times greater.

We may, by winding the coil in different ways, produce more than two poles, but can never produce less than two. Suppose we wind a brass tube or rod from one end to the centre in one direction, and then from the centre to the other end in the opposite direction; on passing a current through such a coil, we shall obtain three poles, two similar ones at the ends and the opposite pole at the centre, this centre pole being equal in strength to the other two combined. These would be called "consequent" poles, and they are used in some forms of dynamos.

With the current running in the same direction from end to end, two opposite poles are produced, one at each end. No alteration is made in the polarity by bending the coil into horseshoe shape; the poles are simply brought closer together, which allows of both poles being utilized in many cases. As in practice it is not often convenient to make the magnetic system of a bent horseshoe shape, it is more usual to build it up, and provide two or more coils for producing the flux. These coils have therefore to be connected up in the right way, for by reversing the connections of one coil we obtain consequent poles, and therefore poles of similar sign at the two ends, as show in Fig. 9. For alternate N and S poles the coils are connected so that, if stretched out straight, the current would be flowing round in the same direction in both coils.

If we take a coil of wire of any given number of turns, wound, say, on a thin brass tube, and send a current through it by connecting its ends to a battery or dynamo machine, a certain

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number of lines of force will be created passing through the core of the coil and round the wire so as to enclose the coil in a magnetic jacket. How many lines of force will be established? This depends on the magnetizing force we bring to bear, and on the magnetic reluctance offered by the magnetic circuit. It will be noticed that this is very similar to Ohm's law for electric currents, for the current that flows depends on the electromotive force, or the current producing force, and on the resistance of the electrical circuit. We can represent the magnetic case in the form of an equation thus—

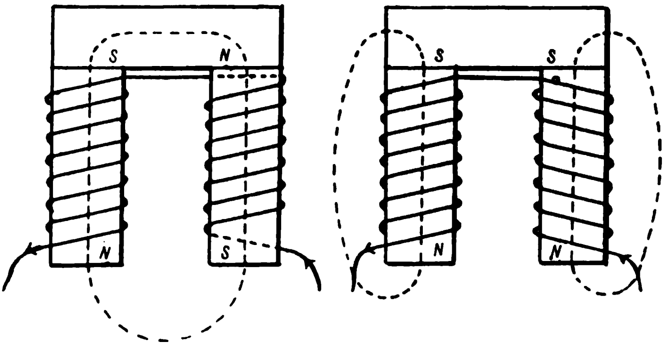

FIG. 9.

$$\text{Total lines of force} = \frac{\text{magnetizing force}}{\text{magnetic reluctance}}$$

The magnetizing force, or the "magneto-motive force" as it is often called, is proportional to the strength of the current and the number of times it circulates round the magnetic circuit. Numerically this is equal to 1·25 times the ampere turns, or 1·25 × amperes × turns of wire in the coil or coils.*

The magnetic reluctance is proportional to the length of the magnetic circuit, inversely proportional to its sectional area, and to the specific permeability of the materials composing it, or—

$$\text{Magnetic reluctance} = \frac{\text{length}}{\text{sec. area} \times \text{permeability}}$$

---

* For the proof of this formula, and others following, the reader is referred to "Elements of Electrical Engineering," by the same author.

We can now give an expression for the total number of magnetic lines produced in terms of the current turns, and the dimensions and nature of the magnetic circuit, thus—

$$\text{Total lines of force produced} = \frac{\dfrac{1{\cdot}25 \times \text{amperes} \times \text{turns}}{\text{length}}}{\text{sec. area} \times \text{permeability}}$$

or, what is the same thing—

$$\left.\begin{matrix}\text{Total mag-}\\ \text{netic flux}\end{matrix}\right\} = \frac{1{\cdot}25 \times \text{amperes} \times \text{turns} \times \text{sec. area} \times \text{permeability}}{\text{length}}$$

The total magnetic flux is usually symbolized by N, and the permeability of the magnetic circuit by μ, and if we keep to the same symbols we can write for the above—

$N = 1{\cdot}25 \times$ amperes $\times$ turns per cm. length of circuit $\times$ sectional area $\times \mu$

The density or intensity of the lines of force, being the number of lines passing through 1 sq. cm. of the section, will be expressed by $\frac{N}{\text{sec. area}}$. Thus, if we have a flux of 1000 lines, and the sectional area of the magnetic circuit, or that part of it under consideration, be 5 sq. cm., then $N = 1000$, but the density $= \frac{1000}{5} = 200$. The density or intensity is usually symbolized by H when the magnetic permeability of the circuit is unity: such circuits are made up of air, brass, gun-metal, zinc, copper, and, in fact, almost all known substances, with the exception of iron in any of its forms, and nickel. It may be taken that any substance which, when brought near to a fairly sensitive compass needle, does not disturb it from the magnetic meridian in which it normally sets itself, is practically non-magnetic, and has a permeability of unity.

The density is often of more importance than the total number of lines of force, for, owing to their self-repellent property, a certain amount of energy must be expended in crowding them into a small space, and usually this is what is required in practice.

NOTE.—The lengths and sectional areas are measured in centimetres and square centimetres respectively, unless otherwise stated. There are 2·54 cm. to an inch and 6·45 sq. cm. to a square inch.

[redacted]

We have seen that $N = 1{\cdot}25$ amp. turns per cm. $\times$ sec. area $\times\ \mu$, and that $H = \dfrac{N}{\text{sec. area}}$, therefore—

$$H = \frac{1{\cdot}25 \text{ amp. turns per cm.} \times \text{sec. area} \times \mu}{\text{sec. area}}$$
$$= 1{\cdot}25 \text{ amp. turns per cm.} \times \mu,$$

which shows us that the density is independent of the sectional area. That is to say, if we want a certain magnetic density in any space, whether the sectional area be large or small, we require a given number of ampere turns to produce it; but the total lines produced may be very different, for this will vary directly with the sectional area. Suppose we require a magnetic density of 100 (*i.e.* 100 lines through each square centimetre) in two cases, where the sectional areas are 100 and 1000 sq. cms. respectively, then, in each case, $H = 1{\cdot}25$ amp. turns per cm. $\times\ \mu$, therefore $100 = 1{\cdot}25$ amp. turns per cm. $\times$ 1.

$$\therefore \text{ amp. turns per cm.} = \frac{100}{1{\cdot}25} = 80,$$

or 80 amp. turns will be required for every centimetre length of the magnetic circuit when the density is 100 throughout. If, therefore, we wind round the magnetic circuit, say, 8 turns to each centimetre length, so as to enclose 100 sq. cms. sectional area, and use a current of 10 amps. in the coil, we shall get 100 lines through each square centimetre, and as we have 100 sq. cms. enclosed, we get a total of $100 \times 100 = 10{,}000$ magnetic lines of force. If we wind the same coil so as to embrace 1000 sq. cms., using the same current, the density will still be the same, viz. 100, but the total lines produced will be $100 \times 1000 = 100{,}000$, though spread over ten times the area. To get the 100,000 lines of force in the former space, the density would have to be increased ten times, and the ampere turns required for each centimetre length would have to be increased ten times also.

In the above cases the magnetic circuit is supposed to be of the same sectional area throughout its length, but if the sectional area varies at different parts, the number of ampere turns required for any given number of lines will be different for the various sections, for the density will vary inversely with the sectional area of each part. We can, however, find the total ampere turns

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required by taking each part separately. First find the density at each part by dividing the total lines by the sectional area. Next measure the length of the magnetic circuit for each particular density, and find the ampere turns for each part as in the above cases. By adding the different values together, we get the total ampere turns for the complete magnetic circuit.

The magnetic reluctance in the case we have been considering, viz. an air space, is fairly high. Iron has a much higher permeability or lower magnetic reluctance than the corresponding length and sectional area of air. Consequently, if we use cores of iron or steel, we get our total lines and our required densities with a much smaller number of ampere turns. It is for this reason that practically all magnetic circuits are built up almost entirely of iron or steel—in fact, the densities employed in dynamo design at the present time would be practically impossible without good magnetic iron or steel.

It has been explained that the permeability of air is taken as the unit, and that the permeability of all non-magnetic materials is the same. A few substances are very slightly less permeable than air, but the difference is so slight as to be of practically no service in insulating any space from magnetic influence. It is therefore seen that we have no real magnetic insulators. Brass, copper, gun-metal, zinc, etc., are often spoken of as magnetic insulators, but they are no better or worse than the same amount of air. The magnetic lines of force will pass through them just as they would through the air if they were removed, so that the introduction of these substances in an air space does not diminish in any way the number of lines crossing the space.

The permeability of iron or steel is a varying quantity, depending on the quality, and it is not always that iron good for magnetic purposes is good for other work. For instance, iron with a certain proportion of nickel in it makes a very good alloy for mechanical engineering purposes; but it is possible to get such an alloy perfectly non-magnetic, though the two elements, iron and nickel, taken separately, are the two most magnetic substances known. It will therefore be seen that great care has to be taken in the manufacture of iron and steel for magnetic purposes, if we wish to get the highest permeability possible.

But the permeability depends also on the magnetic density; the higher we run the density, the less and less permeable does it become.

At a certain low density the permeability of certain brands of iron at present obtainable is over 2000, that is to say, it is more than 2000 times as permeable as air, so that, whatever density we get with an air core, we should get over 2000 times as great a density if we used this particular quality of iron. The permeability of this same piece of iron will fall, however, to a value somewhere near 170 when we have magnetized it up to a density of 17,000 lines per square centimetre, so that, at this density, it is not 2000 times, but only 170 times, more permeable than air; and at higher densities still the permeability falls off at a rapid rate.

The only method of dealing with iron, therefore, seeing that its permeability is a varying quantity for different densities, is to plot curves of the variations in permeability for all the densities commonly employed. The usual method is to plot curves having values of H for the base, and the corresponding density in the iron, usually symbolized by "B," plotted vertically. The value of μ can then be found for any case by dividing B by H.

These curves will usually be supplied by the manufacturers for different brands of iron and steel, and in commencing the design of any particular magnetic circuit or machine we must first select the brand of iron we intend to employ. A typical B-H curve for wrought iron, steel, and cast iron is shown in Fig. 10, with a second base line of values of ampere turns per centimetre, obtained in the following manner.

We have seen that H, the density in non-magnetic materials, is $= 1{\cdot}25$ amp. turns per cm. $\times \mu$, and in this case $\mu = 1$, therefore $H = 1{\cdot}25$ amp. turns per centimetre.

Transposing, we get—

$$\text{amp. turns per cm.} = \frac{H}{1{\cdot}25} = H \times 0{\cdot}8$$

The values of ampere turns per centimetre in the B-H curve (Fig. 10) are therefore each equal to 0·8 times the corresponding value of H. This simplifies the calculations considerably—in fact, no calculations are required, for we simply read off from the curve the number of ampere turns required for each centimetre length of the circuit for any particular density in this particular brand of iron or steel. Of course, a different curve is required when we use other qualities, and where, as is often the case, the

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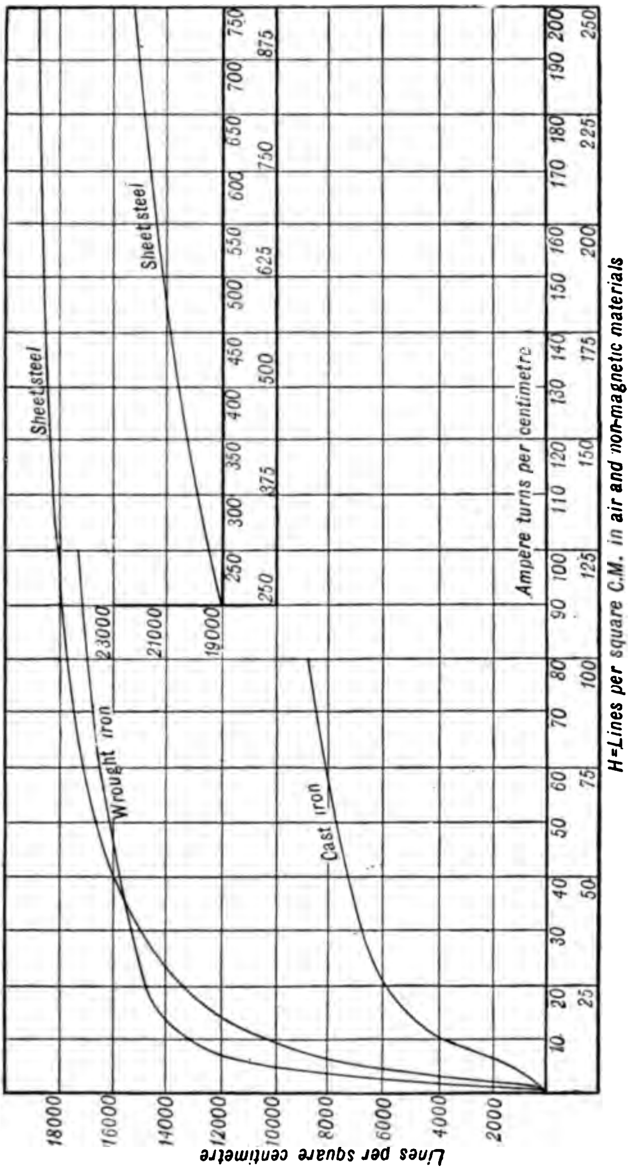

FIG. 10.

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magnetic circuit is made up of different kinds of iron, *i.e.* cast iron, wrought iron, and steel, each part has to be taken separately, and the values obtained from the appropriate curve.

As an example, suppose a magnetic circuit of 100 sq. cm. sectional area for a length of 50 cm., then widening out to 150 sq. cms. for another 50 cms., the whole circuit being made up of wrought iron with permeability corresponding to that given in the curve, Fig. 10; and further, suppose we wish for a total of 1,600,000 lines of force through the circuit, then B for 50 cms. length = $\frac{1600000}{100}$ = 16,000, and B for the remaining 50 cms. length = $\frac{1600000}{150}$ = 10,666. From the curve we find that for a density of 16,000 lines per sq. cm. in this iron, we require 46 amp. turns per cm., while for a density of 10,666 lines per sq. cm., we require 5 amp. turns per cm. Therefore, for 50 cms. at the higher density we require 2300 amp. turns, and for the 50 cms. at the lower density 250 amp. turns, or a total of 2550 amp. turns for the whole magnetic circuit.

The values of H (density in non-magnetic materials for the same ampere turns per cm.) for the two cases are 57·5 for the higher and 6·25 for the lower value, and therefore the permeability of this same iron at the two densities taken $\left(= \frac{B}{H} \text{ in each case}\right)$ will be $\frac{16000}{57 \cdot 5} = 278$, and $\frac{10666}{6 \cdot 25} = 1706$.

In the case where a permeability curve of the iron is not available, a specimen may be prepared and tested by one of various methods. The workshop method consists of turning a piece of the iron to the same dimensions as a standard piece, with which it is compared in a magnetic balance. An instrument of this kind, designed by Fisher-Hinnen, is shown in Fig. 11. The lower part may be fixed to a wall at any convenient height, and this supports, on knife-edges, the balance-arm with sliding weight. A coil of wire, wound on a brass tube with 1 inch bore, is arranged to rest on the lower step, whose surface is very accurately squared up. The standard rod is 1 inch in diameter and 3½ inches long, and when in position inside the coil, the balance arm stands horizontal when brought down to rest on it. The arm is first calibrated in pounds' pull by placing a known weight on the end of the short arm, and marking the position of the slider when the beam just turns. The pull exerted by the magnet, when excited, is proportional to B^2, and therefore the calibration of the arm can be made in terms of B; for—

$$B = 1317\sqrt{\frac{\text{pull in pounds}}{\text{area of core in sq. inches}}}$$

The ammeter supplied with the instrument is usually calibrated in ampere turns per centimetre, for the turns in the coil being fixed, the ampere turns, and therefore values of H, will vary directly with the current. For low values of B, a weight is hung on the end of the short arm, and a constant used with the readings obtained, or a second scale engraved. To use the instrument, the sample is turned to the exact size of the standard bar, and perfectly square at the ends. A few accumulators and an adjustable resistance are connected in the circuit, and the bar placed inside the coil. The sliding weight is then brought close to the fulcrum, and the lever brought down on the end of the bar. The current is now slowly increased by cutting out some of the resistance, one step at a time, and the slider gently moved till the lever breaks away. The value of B is then read on the arm, and the corresponding value of H or ampere turns per centimetre on the ammeter scale. This should be repeated two or three times

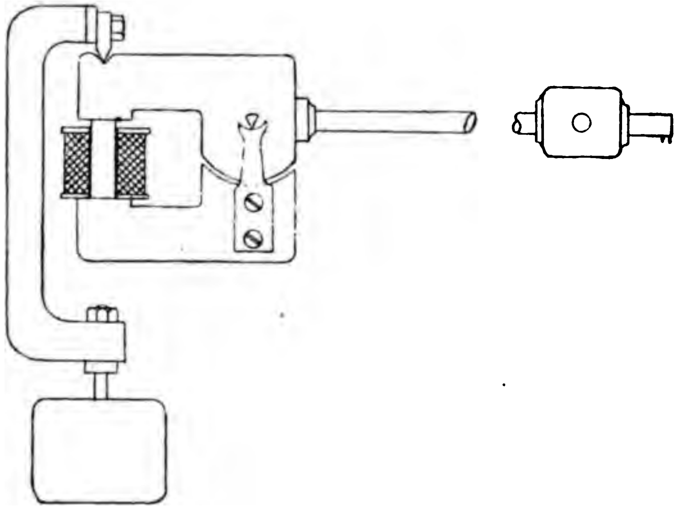

FIG. 11.

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to obtain a good mean value, and the same should then be done for *increasing* values of B. A series of descending values may also be taken by increasing the current beyond the point required to hold the armature down with the slider at the highest point desired, and then slowly reducing the current till the lever breaks away.

Several instruments of this kind are in common use, designed by Professors Ewing, Thompson, and others, and are all easy of manipulation, enabling a complete curve to be obtained in a short time once the specimen is turned ready. Where such an instrument is not available, a measurement, involving a little more time, may be made to get the same results. In this case the specimen should be turned into a rod about 1 yard in length, and wound evenly all over with a single or double layer of insulated wire, being careful to count the total number of turns put on. The length and sectional area of the rod being accurately measured, the turns per centimetre length are found by dividing the total number of turns by the length in centimetres. If now a current be passed through the coil, the number of lines of force per square centimetre in the iron will be $B = H \times \mu_1 = 1{\cdot}25$ amp. turns per centimetimetre $\times\ \mu$.

But B is equal to $\dfrac{\text{total lines}}{\text{sect. area}}$

$$\text{Therefore } \frac{\text{total lines}}{\text{sect. area}} = 1{\cdot}25 \text{ amp. turns per cm.} \times \mu$$

$$\text{and therefore } \mu = \frac{\text{total lines}}{1{\cdot}25 \text{ amp. turns per cm.} \times \text{sect. area}}$$

The total lines may be measured by noting the deflection produced by the magnetized bar on a sensitive magnetometer, consisting of a small compass needle attached to a long aluminium pointer which moves over a degrees scale. To do this, fix the long bar and coil in a vertical position, with one end a few centimetres away from the magnetometer needle, and in a plane at right angles to the magnetic meridian, or the plane in which the needle sets when undisturbed. The other end of the bar will then be far removed, and when magnetized by a current in the coil, the pole formed at the far end will be in such a position as to have little or no turning effect on the needle. The deflection obtained will therefore be that due to one pole only.

The coil is now to be connected to a battery of accumulators, an ammeter, an adjustable resistance, and a reversing key, as shown in Fig. 12. A small current is switched on, and the deflection of the compass noted. The current is then reversed, and the reversed deflection and also the value of the current noted. The mean value of the two deflections is the correct deflection for that particular current. The current is now increased in small steps, and the operations and observations repeated with each change in the current up to the highest magnetization desired.

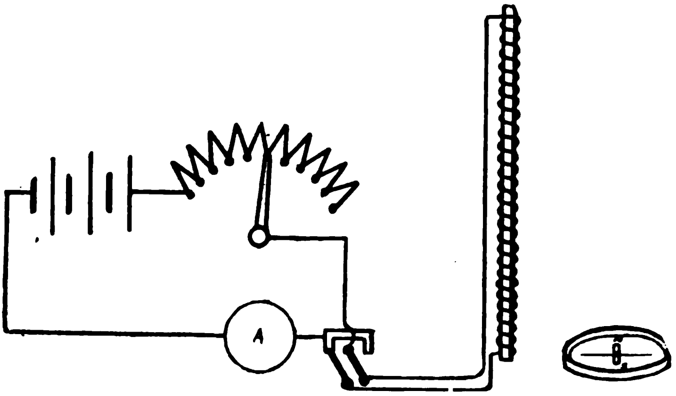

FIG. 12.

The distance in centimetres from the centre of the bar to the centre of the compass needle must be noted, and if it has been found advisable to alter this as the test proceeded, owing to the deflection becoming too large, the altered distance must also be noted. The observations are best entered in a table.

Distance from bar to needle in centimetres.	Current in amperes.	Ampere turns per centimetre.	Deflection.			E_A × tan deflection = 0·18 × tan deflection.	Strength of pole.	Total lines.	Values of B.	Values of H = 1·35 ampere turns per centimetre.	Values of μ.
			Right.	Left.	Mean.						

[redacted]

The force exerted by the magnetized bar, at the point occupied by the compass needle, is equal to the strength of the pole formed at the end divided by the square of the distance from the centre of the bar to the centre of the needle. This force is also equal to the horizontal component of the earth's magnetic field multiplied by the tangent of the angle of deflection. For most places in England, free from iron, the earth's horizontal component has a value of 0·18, and is symbolized in the above table by E_h. We therefore get—

$$\frac{\text{strength of pole}}{d^2} = 0{\cdot}18 \times \tan \alpha$$

$$\text{therefore strength of pole} = 0{\cdot}18 \times \tan \alpha \times d^2$$

Pole strength is measured in units, each containing 4π or 12·56 lines of force.

$$\text{Therefore total lines} = N = \text{strength of pole} \times 12{\cdot}56$$

$$\text{and } B = \frac{N}{\text{sect. area}}$$

$$\text{while } H = 1{\cdot}25 \text{ amp. turns per cm.}$$

$$\text{and } \mu = \frac{B}{H}$$

[redacted]

CHAPTER III

THE PRODUCTION OF AN ELECTROMOTIVE FORCE

THE magnetic circuit of all dynamos has to contain certain air gaps to permit of the conductors being driven through the magnetic field, and though these air gaps form a very small proportion of the total length of the magnetic circuit in every case, their permeability being unity and the density through them fairly high, the total number of ampere turns required is often increased to considerably over double of what would be required if the magnetic circuit had been entirely of iron.

It is owing to this great increase in the excitation required that the air-gap density is never run to such high values as is commonly employed in the iron portions.

When the lines of force enter the air gap they naturally spread out, owing to their self-repellent action and the high reluctance of the air space. The amount of spreading depends on, and is proportional to, the length of the air gap (Fig. 13). This is true, so long as we are dealing with the short lengths commonly employed in dynamos. The sectional area of the air gap is therefore often considerably greater than that of the iron boundary surfaces, so that the density in it is, in most cases, considerably reduced. The rule for calculating the effective sectional area is to imagine the sectional area of the iron bounding surfaces to be increased by 0·8 times the length of the air gap added in every direction; thus, suppose an iron core, rectangular in section, 12 inches by 10 inches, giving 120 square inches for the area of the iron bounding surface, with an air gap 0·3 inch in length, the sectional area of the air gap would be found by adding 0·8 times 0·3 = 0·24 inch to *each side* of the iron, making 12·48 inches by 10·48 inches, practically 130 sq. inches. The magnetic lines actually spread through a much greater area than that given by the above rule, but those that do not cross through the area so obtained are considered as waste lines, for they will be outside the range of the dynamo conductors, and therefore of no service in generating an electromotive force in them.

It will therefore be seen that if we require a given number of magnetic lines of force in the armature, useful for developing the electromotive force, we must make provision for a larger number in the remaining portions of the magnetic circuit, so as to allow for the waste lines, brought about principally by the necessity for the air gaps, and from the fact that for practical reasons the ampere turns providing the magneto-motive force for the circuit enclose but a small proportion of its total length. In modern dynamos it is usual to provide from 15 to 30 per cent. more lines than are required in the armature, to allow for magnetic leakage. This is spoken of as the *leakage factor*.

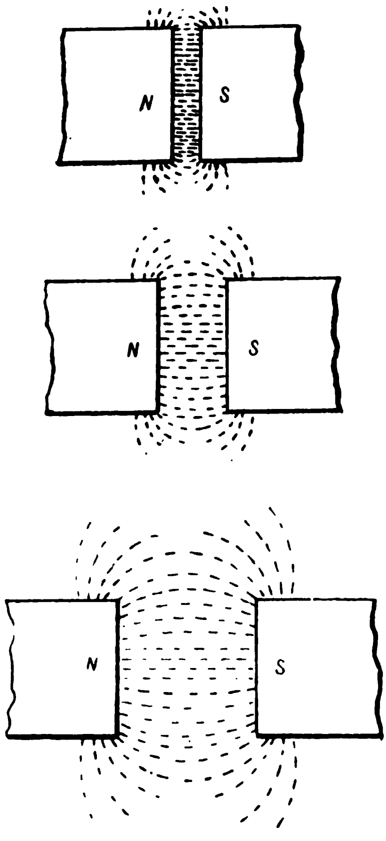

FIG. 13.

The method of calculating the excitation here outlined will have to be considered in much greater detail later, but we must leave it for the present to consider several important points underlying the action and design of dynamos.

Consider a magnetic field existing between the parallel pole faces of a fairly strong magnet, as represented in Fig. 14. The lines inside will be straight, and uniform in density. If the density were greater at one part than another, the reluctance at that part would be greater, and the lines of force would spread out so as to find paths of less reluctance, for the lines in passing from point to point always pass in the path of least reluctance, and where they divide they do so in inverse proportion to the reluctance of each path. If the iron surfaces are not parallel and smooth, the density will not be uniform, for where the gap is shorter more lines will cross before the reluctance at that part is equal to that where the gap is wider. The density will therefore increase at the narrower part of the gap and decrease where it widens out.

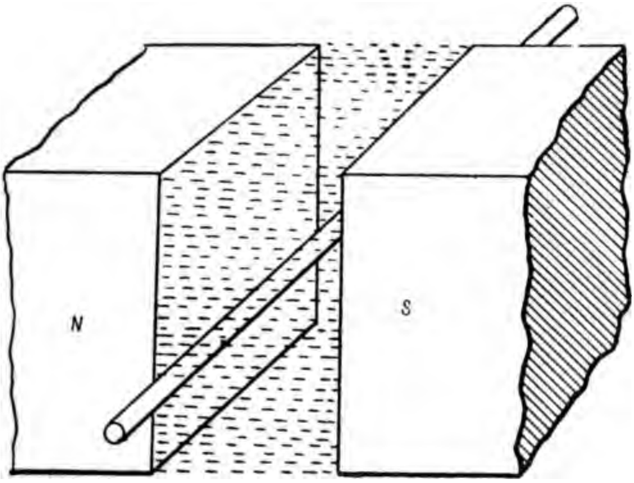

FIG. 14.

Suppose that inside this field we introduce a copper conductor standing at right angles to the field, this will have no influence on the field in any way, providing it be carrying no current. We have seen that its magnetic permeability is unity, and therefore the magnetic lines will pass through it exactly as they did through the air which it has displaced. If we move the conductor about in the magnetized space, we shall feel no restraint or any action to indicate that we are moving it in anything but the ordinary atmosphere. The moment we send a current through the wire, however, we notice a difference. The conductor endeavours to move out of the field, and if we are to retain it in the field we have to exert a certain force to do so. The force exerted by the conductor in its effort to move is proportional to the field strength and to the value of the current flowing in the conductor.

When we send a current through the conductor we establish a second magnetic field round it. This second circular field combines with the first straight field to produce a resultant which is a considerable distortion of both. Now, it is a property of magnetic lines that they always tend to shorten. To keep them distended, as it were, we have to exert a certain force, and the current-carrying conductor produces a magnetic field which distorts and considerably elongates many of the lines of force crossing from face to face. The consequence is that the lines, in their endeavour to straighten out, bring a force to bear on the conductor tending to throw it out of the field. This is shown in Figs. 15 and 16. In Fig. 15 we have the conductor carrying a current, but standing outside the field, the direction of both fields being marked by arrows. In this case the current is supposed to be flowing down the conductor, and, according to the "screw" rule, a north pole would therefore be urged round it in a clockwise direction, as seen from the top. In the second or straight field a north pole is always repelled from the north towards the south pole. In Fig. 16 the current-carrying conductor is placed between the poles of the magnet, and the magnetic distortion produced is indicated by the curvature of the lines. The conductor in this position is being urged downwards in the direction of the arrow.

A second conductor carrying the same current would experience a similar force, and if these two conductors be insulated from each other and bound together, the force exerted on the two will be double that on each taken singly. This applies to any number of conductors, providing they are carrying currents in a similar direction. If the direction of the current be reversed, the direction of its field is also reversed, and consequently the direction of the magnetic distortion will be such as to urge the conductor up instead of down. It will therefore be seen that if the conductors in the field be carrying currents in opposite directions there will be a differential action between them, and the combination will move in a direction corresponding to that produced by the resultant force. If the current and the direction of the field be both reversed, the conductor will be urged in the same direction as before the reversals.

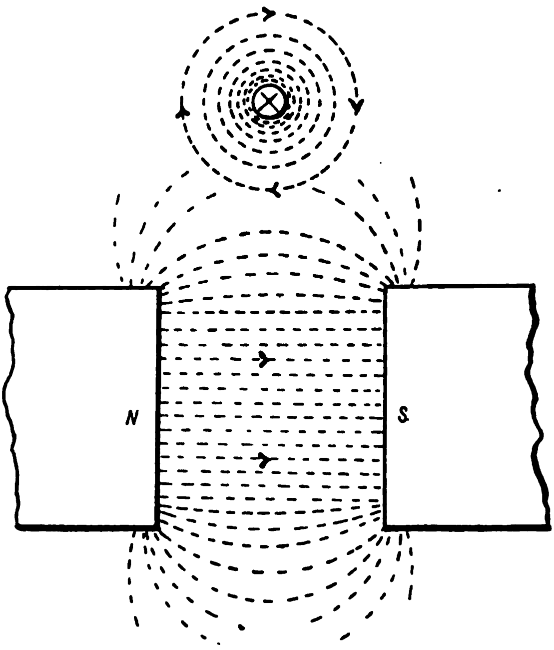

FIG. 15.

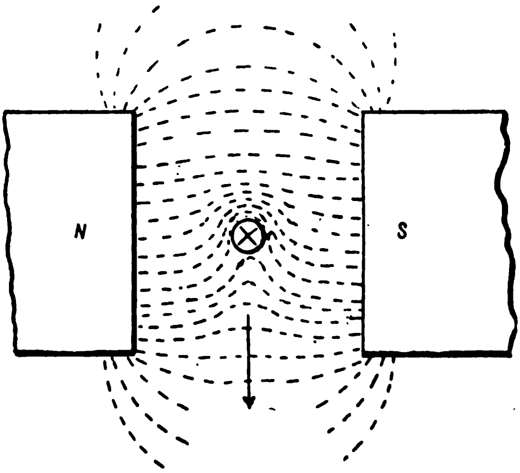

FIG. 16.

Imagine a field of unit strength, *i.e.* one line of force per square centimetre. If into this field we introduce a conductor 1 cm. long, carrying a current of 10 amps., the force exerted on it will be 1 dyne. This is a very small force, only the $\frac{1}{444393}$ part of the force exerted by a pound weight, but the field is very small also, and the conductor very short. We have seen that it is easy to produce fields of several thousands of lines to each square centimetre. The dyne, however, is the unit of force for scientific purposes, and the unit of work is the "erg," which represents the work done against a force of 1 dyne through 1 cm. If we therefore move the conductor through 1 cm. against its tendency to go in the opposite direction, we shall do 1 erg of work.

Now, work done is equal to QV, or the quantity multiplied by the potential through which we raise it, and therefore V = work done divided by Q.

If we take one second in doing the one erg of work we shall have acted on 10 coulombs of electricity, *i.e.* on one absolute unit quantity, and, it will be noticed, we shall have cut through one line of force. A certain electromotive force will have been induced in the conductor, such that $V = \frac{\text{work done}}{Q} = \frac{1}{1} = 1$ absolute unit. Suppose the field to be increased to ten times its former value, then in each sq. cm. of its section there would be ten lines of force, and the force acting on the same conductor would be 10 dynes. The work done in moving it 1 cm. would be increased to 10 ergs, and consequently the electromotive force induced in it would be $= \frac{\text{work done}}{Q} = \frac{10}{1} = 10$ absolute units. Again, suppose the time taken in moving the conductor be $\frac{1}{10}$ second, the work done will still be the same, but the quantity acted on it this time will be only $\frac{1}{10}$ the former quantity, therefore $V = \frac{10}{\frac{1}{10}} = 100$ absolute units. The result is the same whatever current we suppose to be flowing in the wire, even if it be reduced to an infinitely small current; thus, suppose in the first case the current be $\frac{1}{100}$ amp., *i.e.* $\frac{1}{1000}$ absolute unit. The force acting on the conductor is then $\frac{1}{1000}$ of the former value, and therefore the work done in moving it 1 cm. against this force is only $\frac{1}{1000}$ of its former value. The total quantity acted on in 1 second is also $\frac{1}{1000}$ part of its former value, so that

[redacted]

$V = \frac{\text{work done}}{Q} = \frac{\frac{1}{1000}}{\frac{1}{1000}} = 1$, the same value as before. It follows, therefore, that the electromotive force induced in this way depends only on the total lines of force cut, and on the rate of movement of the conductor. This is the underlying principle of all dynamos.

No electromotive force is induced if the conductor be moved sideways through the field, so as to slide through the lines without actually cutting them, for in this direction there is no force acting on the conductor, and therefore no work is done in moving it. If it be moved obliquely through the field, as shown in Fig. 17, it is only the vertical component which is effective, and the lines cut during the time in which the conductor is moving over the distance *a* would be represented by the conductor moving vertically over the distance *v* in the same time.

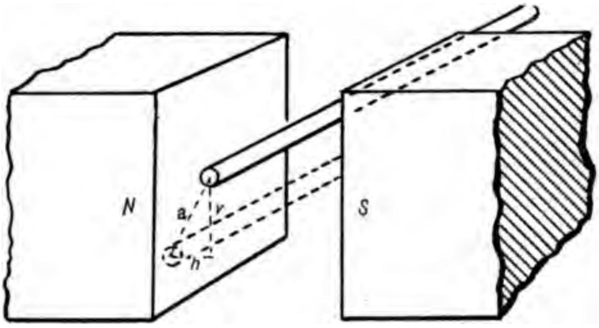

FIG. 17.

The electromotive force induced has a particular direction, one end of the conductor being raised and the other lowered in potential. A current always flows from the point of higher to a point of lower potential in conductors outside the dynamo, but in the opposite direction in the dynamo armature conductors; it being the special work of such machines to raise the potential under the action of a flow of electricity which tends always to equalize potentials.

The point of higher potential is usually called the *positive* end, while the point of lower potential is called the *negative*. These are symbolized by + and − respectively. Outside the dynamo the current always flows from + to −, while inside it flows from − to +.

[redacted]

The direction in which a current will flow in a conductor under the electromotive force induced in it depends on (1) the direction of the field, and (2) the direction of motion of the conductor. It has been shown that a motion at right angles to the field, or a component in that direction, is essential, but if the conductor be moved at right angles, first in one direction, and then in the reverse, the electromotive force induced in it will reverse also, and the current with it, if it forms part of a closed circuit. We therefore have three things to consider, each acting at right angles to the other two: first, the direction of the field; second, the direction of motion of the conductor in the field; and third, the direction of the current which flows under the electromotive force induced in the conductor. These can be represented very conveniently by the fingers and thumb of the right hand. If the hand be outstretched, the thumb normally lies at right angles to the fingers. If, keeping the first finger in its normal position, we bend the other three fingers at right angles, we get three right-angled directions indicated, which can therefore represent the three things mentioned above. Let the first finger point in the direction of the field (from N. to S.), the thumb in the direction

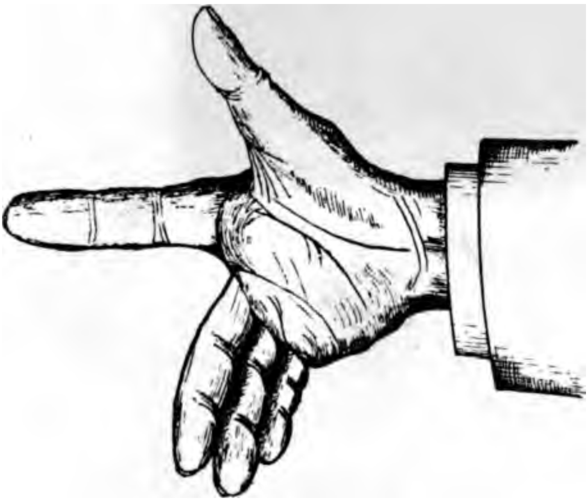

FIG. 18.

[redacted]

of motion of the conductor, then the remaining three fingers point in the direction in which a current would flow in the conductor (see Fig. 18).

If the conductor be rotating within the poles, then the electromotive force induced will vary from nought at *a* and *c*—where for a short time it is simply sliding through the field—to a maximum value 90° beyond this point (see Fig. 19). At the position *a* and *c* its movement has no vertical component, while at 90° to either side, in position *b* and *d*, there is no horizontal component, and the rate of cutting, with uniform rotation, is therefore a maximum at these points. It will be seen that, if we imagine a uniform field and a uniform motion of the conductor, the rate of cutting, and therefore the electromotive force, will vary with the sine of the angle of rotation. Starting at nought, the electromotive force rises slowly to a maximum value at 90°, then slowly declines to nought at 180°, rising again to a maximum value at 270°, but in the reverse direction, and again falling to zero at 360°. The electromotive force changes, if plotted in a curve, would therefore be of the form shown to the right of Fig. 19. If in the position *b* or *d* we cut through, say, 1000 lines in moving the conductor 1 cm., then in the same time, at 30° and 60° from zero, we shall cut through 1000 × sine 30° and 1000 × sine 60°, or 1000 × 0·5 = 500, and 1000 × 0·866 = 866 lines, and the electro-motive forces induced will be in the same proportion. Each revolution would give rise to a similar wave of electromotive force, and if the conductor formed part of

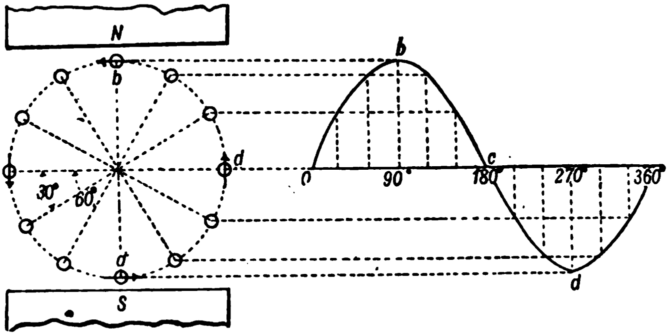

FIG. 19.

a closed electrical circuit, a current would flow in it having the same characteristics as the electromotive force wave in Fig. 19. This would be called an *alternating current*, and the dynamos employed for generating alternating currents are called "alternators." To complete the circuit, and so obtain an alternating current, all that is necessary is to attach the ends of the conductor to two insulated rings fixed to the rotating shaft, with brushes pressing on them, to which the circuit outside the dynamo may be connected (Fig. 20).

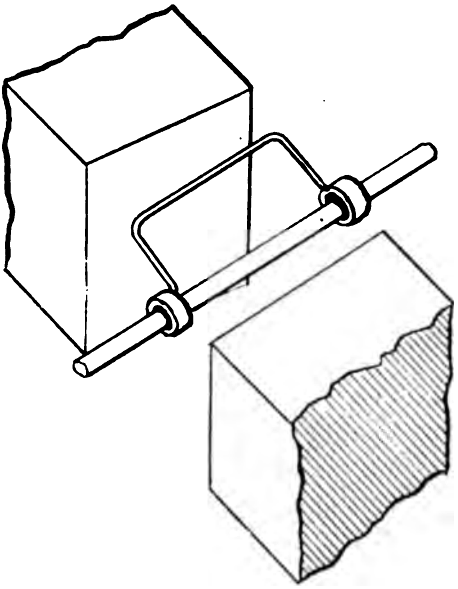

FIG. 20.

Some support would, of course, be necessary for the wire, and by making this of iron, we, at the same time, are enabled to obtain a very considerable increase in the flux through which the conductor cuts when rotating, for the magnetic reluctance of the circuit in Fig. 20 would be very great compared with that in Fig. 21. Here the internal space is practically filled with iron, and the pole pieces are shaped so as to embrace it for a considerable distance. This iron is spoken of as the "armature core." For mechanical reasons the core has to rotate with the

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wire, otherwise it could not form a support for it. This does not alter the magnetic flux through it in any way, for the lines of

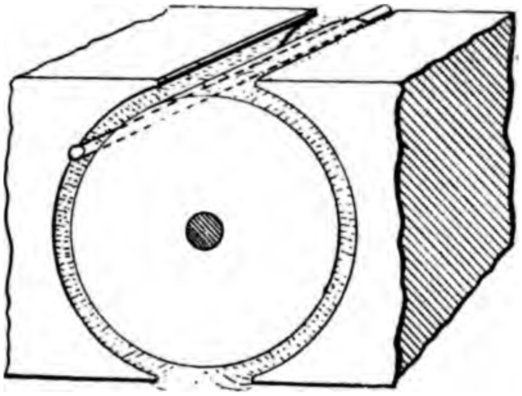

FIG. 21.

force remain stationary in the iron as it rotates. The iron, however, cuts through the field, as does the conductor, and therefore an electromotive force is induced in it, and a large

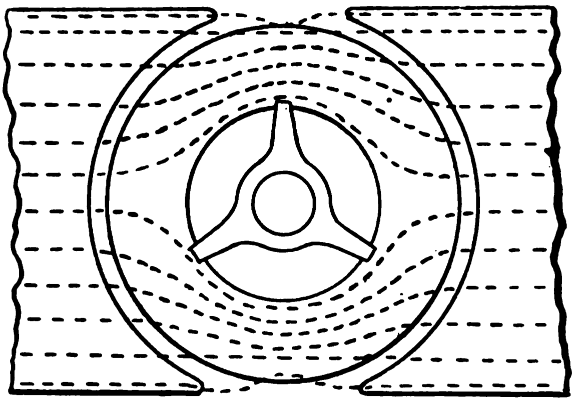

FIG. 22.

current would circulate round it, unless prevented in a manner to be explained later.

There is no necessity to fill the entire space with iron, and in large machines this is never done. Rings of iron, attached to the rotating spindle by a spider casting, would provide a sufficiently easy path for the lines of force, and has a decided advantage over the former, as we shall see. The lines of force then divide through the two halves of the ring, while very few pass through the central portion, especially if the depth of the ring be sufficiently great (Fig. 22).

The shaping of the pole pieces in this way will have altered the distribution of the lines of force. The field will now be practically uniform and radial inside the iron boundary, besides being, as explained above, very much more intense for the same excitation. The alternating nature of the electromotive force induced will, however, be the same as before, for the conductor will be cutting the field at the maximum rate when it has no horizontal component in its movement, *i.e.* at the centre of the pole pieces and at the minimum rate when at right angles to this position; but owing to the more radial direction of the flux, the electromotive-force wave will be more or less flattened at the top, for the maximum rate of cutting will be maintained for a longer period.

In a great many cases, however, it is not an alternating current that we require, but a steady or continuous current. Now, we have seen that while the conductor is cutting through the field in the same direction, the electromotive force induced is continuous, and only reverses as we reverse the direction of cutting. If we could therefore move the conductor during its rotation always in the same direction through the field, we should induce a continuous electromotive force in it. The only way to accomplish this would be to arrange the field radially inwards or outwards all the way round, as shown diagrammatically in Fig. 23. The conductor in rotating would then be cutting the field always at the same rate and in the same direction, and therefore we should induce a constantly directed and uniform electromotive force.

The electromotive force induced by one conductor in this way is usually small; for in practice the speed is limited, and the intensity of the field in the air gap cannot be made very high. It may be increased by using more conductors, connecting them up so that the positive end of one is connected to the negative end of another; the electromotive forces induced will then add together. But this can only be done by connecting each conductor to a separate pair of insulated rings on the shaft, and by means of brushes, which make connection to them as they rotate, connecting the various conductors together outside the machine. We should, however, soon arrive at a limit to the number of conductors that could be connected up in this way, owing to the space occupied by the rings and brushes, and therefore for higher electromotive forces a different arrangement has to be made. Machines of this type are known as "Homopolar" dynamos.

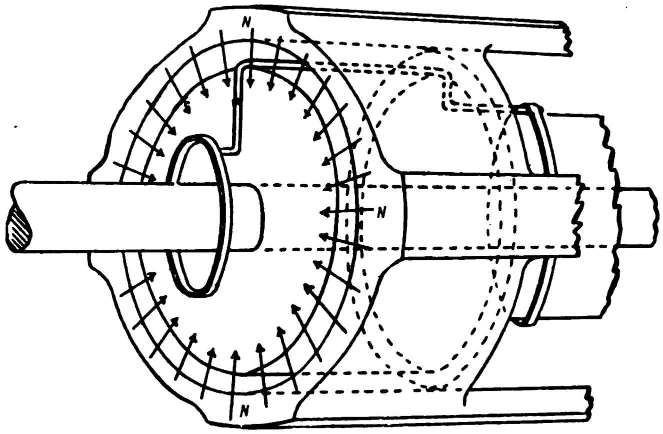

Fig. 23.

They are very seldom used, owing to the drawbacks mentioned above, though there may be a future for them in connection with turbine driving, where exceptional difficulties are met with in employing ordinary types of machine, owing to the high speeds employed.

We may now consider how higher electromotive forces can be produced to give continuous currents in the circuit. Fig. 24 represents a coil wound round a ring core. Each conductor on the outer face is cutting through the field in the same direction, and therefore inducing the same electromotive force. There being practically no field in the interior space, the conductors in that region are not developing an electromotive force. This, however, is just what we require, for if the inside conductors cut through the field also, an electromotive force would be induced in them in the same direction as in those on the outer face. They would, therefore, be in opposition the one to the other; but as it is, the conductors inside act as connectors, joining the + end of one conductor on the outside face to the – end of the next, which is necessary if the electromotive forces are to add together.

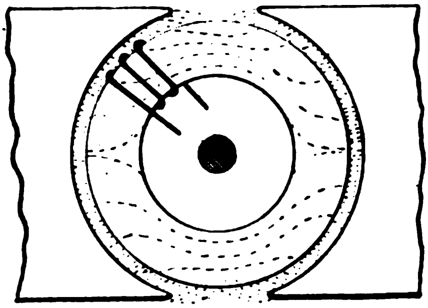

FIG. 24.

But the coil, like the single conductor, will reverse in its electromotive force as it changes its direction of motion through the field, and give rise to an alternating electromotive force. We might, however, provide a single insulated split-ring, instead of two

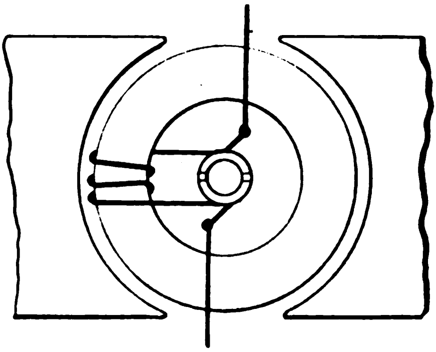

FIG. 25.

insulated rings, on the shaft connecting each end of the coil to one of the parts. With two brushes touching the ring across a diameter, we can now make connection to the outside circuit as before, and in this case the electromotive force, though reversing in the coil at each half-revolution, will be constant in direction in the outside circuit (Fig. 25). This, it will be noticed, is a simple mechanical device for reversing the connections of the coil to the outside circuit just at the moment that the electromotive force is reversing in the coil. The curve of electromotive force is therefore changed for the outside circuit, as shown in Fig. 26. This device is known as a "commutator."

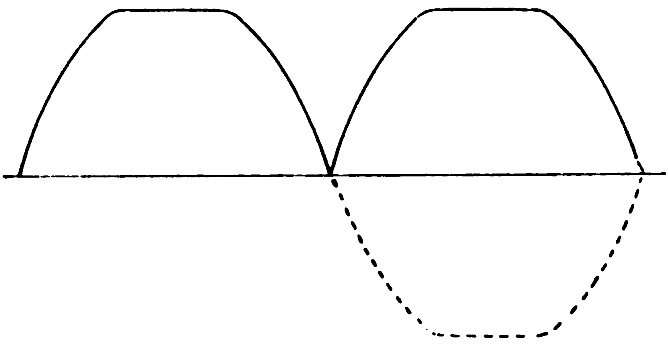

FIG. 26.

The space on the armature core might be further utilized by winding a second similar coil directly opposite the first, and connecting it to the same two parts of the split-ring commutator, in such a manner that the two electromotive forces are in opposition in respect to the separate coils, though acting together, in parallel,

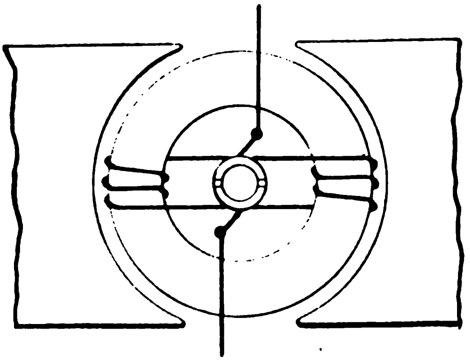

FIG. 27.

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in the outside circuit, as shown in Fig. 27. The capacity of the machine would now be doubled, for, though the electromotive force would be no higher with the two than with one coil, the maximum current we may take from the machine has been doubled, for each coil will now carry half the total. The resistance of the armature coils has also been reduced to half by the addition of the second coil in parallel.

The number of turns of these two coils might also have been increased, till each occupied half the total armature circumference. The electromotive force induced by each coil would then have been correspondingly greater, though we should still have the very fluctuating electromotive force represented by Fig. 26, which can scarcely be called continuous, seeing that it dies down to zero twice at each revolution. A very much better arrangement would be to divide the winding into four coils, and connect them to a four-part commutator, as shown in Fig. 28. The electromotive force will now be as great at its maximum value as it would have been with the same winding connected to the two-part commutator; but there is the very great difference, that now it never falls to zero, for at the time when one pair of coils is reversing in electromotive force, the other is developing its maximum value, and as this begins to die down, the electromotive force in the first begins to rise, and has attained its maximum by the time the second has fallen to zero. It will therefore be seen that, by this arrangement, the variations in the electromotive force throughout a revolution have been very considerably reduced. In fact, the variations with the four-part commutator are not much greater than quarter of what they were

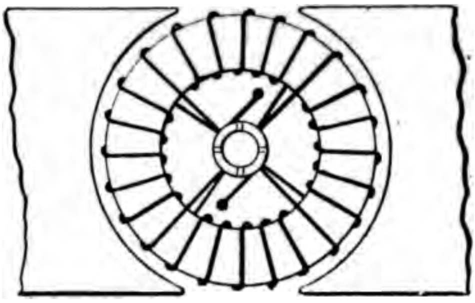

FIG. 28.

[redacted]

with a two-part commutator and the same winding. The curves of electromotive force for each pair of coils, and the resultant electromotive force, are shown in Fig. 29.

It will be seen, without further demonstration, that if we provide more parts to the commutator, and so divide the winding into a greater number of parts, the fluctuations in the electromotive force at the brushes will be still further reduced, so that with thirty parts in the commutator, the variations are scarcely more than 1 per cent. of that with a two-part commutator. This subdivision of the armature winding, with separate commutator bars for each, is exactly what we require from other important considerations. We therefore find that for two poles, as represented in Fig. 28, sixty or more commutator-segments are allowed, and the winding divided up so that each coil forms but one or two turns. In this case the variations in the electromotive force are so exceedingly small that great refinements are required to detect them at all, and so we have obtained from our alternating armature current a continuous current for the outside circuit.

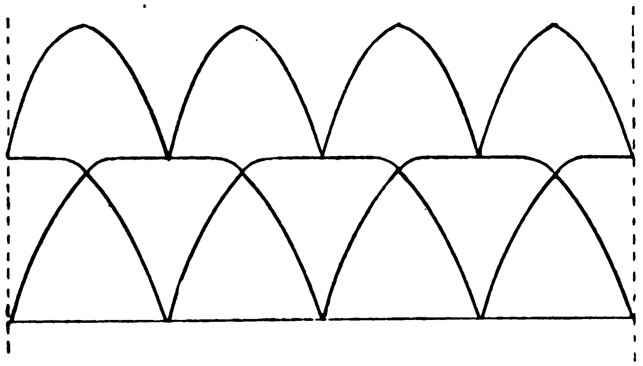

FIG. 29.

Consider the electromotive force induced by such an armature. This, as we have already seen, depends on the rate of cutting magnetic lines by conductors. Now, in one revolution each conductor cuts through the field twice, and will make a certain number of revolutions and double cuttings each second. Let N equal the number of lines of force crossing the armature or emerging from one pole, then the lines cut by each conductor per revolution will be = 2N. Let S equal the number of revolutions per second, then the rate of cutting by each conductor will be = 2NS per second, and if there be C conductors in series, each will be cutting at the same rate, and adding its electromotive force, therefore the mean electromotive force induced will be = 2NSC.

But C conductors in series will represent only half the total number on the armature face, for the brushes connect the two halves in parallel. If, therefore, C is used to represent the total number of conductors on the armature face, we have—

$$\text{Electromotive force induced} = \frac{2\text{NCS}}{2}$$

This, being in absolute units, must be also divided by 10^8 to bring it to volts, and therefore we arrive at the formula for the two-pole machine, viz.—

$$\text{Electromotive force in volts} = \frac{\text{NCS}}{10^8}$$

It will be noticed that this value is constant in this case, for as a coil moves from one side to the other, its place is taken by another, thus maintaining a constant number of conductors between the brushes that are cutting through the field in the same direction.

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CHAPTER IV

FUNDAMENTAL PRINCIPLES OF ALTERNATING CURRENTS

WITH alternators and alternating currents we have to deal with effects which do not appear in direct current work. The electromotive force and current are continually varying in magnitude, and we must first decide what value of the alternating wave corresponds to a particular direct current maintained for the same time. Each complete wave or "cycle" corresponds to a certain amount of work, and if this be the same as the work done by a direct current flowing for the time corresponding to one cycle, then the alternating current would be equivalent to that particular direct current.

Now, work done is equal to C^2Rt, where C = current in amperes, R = resistance in ohms, and t = time in seconds; for work done = power × time, and therefore is $= E \times C \times t$, and by Ohm's law $E = C \times R$, and therefore $E \times C \times t = C^2 \times R \times t$. Taking, then, the time corresponding to one complete cycle, the mean value of the alternating current *squared* when passed through any given resistance (a lamp for instance) will be equal to the direct current squared passed through the same resistance, when the work done by the two is the same, or in the case of the lamp, when the light given out is the same for the two, Therefore the direct current squared is equal to the mean value of the alternating current squared, taken throughout the cycle, or—

$$(\text{Direct current})^2 = (\text{mean alternating current})^2$$

therefore—

$$\text{Direct current} = \sqrt{\text{mean square of alternating current}}$$

This "root mean square value" is sometimes spoken of as the "effective" value of the alternating current, and may be found by dividing the cycle up into a number of equal parts, squaring

[redacted]

the values of each, then taking the mean or average value of these squared values and finding the square root of the value so obtained. If this be done for a sine curve as shown in Fig. 19, we get—

$$\text{Effective value} = \text{maximum value} \times \frac{1}{\sqrt{2}}$$

therefore—

$$\text{Effective value} = \text{maximum value} \times 0{\cdot}707$$

When the curve of electromotive force, or current, does not follow a sine law, the effective value will approach nearer to the maximum value the more flat topped the curve becomes, and the more peaked the curve the greater will be the difference between the effective and maximum values. The ratio between these two quantities has been called the "amplitude factor." The variation between the mean value and the effective or root mean square value also depends on the form of the alternating wave, and the ratio between these is known as the "form factor." We have, therefore —

$$\text{Amplitude factor} = \frac{\text{effective value}}{\text{maximum value}}$$

and—

$$\text{Form factor} = \frac{\text{effective value}}{\text{mean value}}$$

For a sine curve, these have the values—

$$\text{Amplitude factor} = \frac{\frac{1}{\sqrt{2}}}{1} = \frac{1}{\sqrt{2}} = 0{\cdot}707$$

$$\text{Form factor} = \frac{\frac{1}{\sqrt{2}}}{\frac{2}{\pi}} = \frac{\pi}{2\sqrt{2}} = 1{\cdot}11$$

In the direct-current dynamo, the power delivered is equal to the current in amperes × pressure in volts, and the same applies to alternators if delivering current to lighting circuits only, but for most cases, with alternating currents, we have to put in another factor in finding the power delivered, known as the "power factor," so that alternating power = E × C × power factor. This arises from the fact that in all circuits containing electro magnets the current is not in step, or in "phase," with the electromotive force, but lags behind it by a certain amount.

To understand this—which is a point of very great importance in the design and performance of all alternators—consider a coil of wire surrounding an iron core, forming an electro magnet. We have seen that whenever conductors are cut by a magnetic field an electromotive force is induced in the conductors. If we apply a small direct electromotive force to the ends of the coil a current will flow in it, but this current creates a certain number of lines of force, springing through the core and encircling the coil. These lines of force, therefore, induce an electromotive force in the coil independent of that giving rise to the current. Now, this induced electromotive force is opposed to that producing it, and therefore the growth of the current is retarded by the magnetic field it has to produce. In the circuit we are considering the field would be large, and therefore the current would take quite an appreciable time in rising to its full value, whereas if the same circuit were without its iron core, the current would rise to the same final value in a much shorter time, and if the coil were unwound from the iron core, and twisted backward and forward in zigzag fashion, there would be very little magnetization produced, and the rise of the current to its final value would be almost instantaneous on the application of the electromotive force.

With an alternating electromotive force applied to the coil, the current never reaches the value it would finally have with a similar-strength direct electromotive force, for the former is continuously varying.

When the electromotive force is removed, the current, instead of stopping instantly, is maintained for a certain time under the electromotive force induced by the lines of force cutting the conductors as they die away. It will thus be seen that, not only is the alternating current less than it would be in the same circuit, using the same value of direct electromotive force, but the current lags behind the pressure all through the cycle. This is shown by the curves of direct and alternating electromotive force and current in the same circuit in Fig. 30, and it will be noticed that the lagging effect is only of importance, in direct current work, at the time of starting and stopping the current, whereas in alternating current work, the current being started, stopped, and reversed continuously, the effect is of the utmost importance.

It will be seen that Ohm's law in its simple form cannot be applied to an alternator, for there may be another factor in addition to the resistance tending to reduce the value of the current. This is usually spoken of as the *inductance* of the circuit. If the circuit is of such a nature that any particular current is able to induce a large number of magnetic lines of force linked with it, its inductance is large. It will therefore be seen that the inductance of a circuit is a thing depending on its nature, *i.e.* whether it contains large electro magnets with massive iron cores, and many or few turns of winding, and its value is fixed once the circuit is completed, except in so far as it is affected by changing permeability.

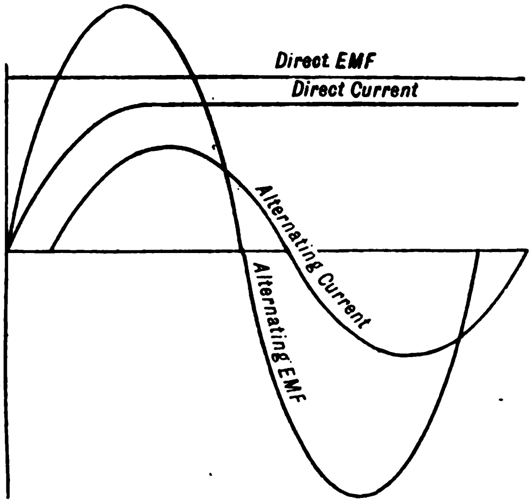

FIG. 30.

The actual diminution in the magnitude of the current obtained under any given alternating electromotive force can be considered as due to the back electromotive force induced in the circuit, but this depends not only on the number of lines of force induced and the number of turns through which they interlink, but also on the *rate* at which the interlinking takes place. If N

[redacted]

represents the total lines of force induced in the circuit, and T the total turns with which they interlink, then the electromotive force induced = N × T × rate of interlinking.

The inductance of the circuit is usually measured in "henries," and is symbolized by L. A circuit has an inductance of 1 henry when 1 amp. produces such a number of magnetic lines of force that the interlinking of lines and turns produced by it is 100,000,000. If the permeability of the circuit remains constant, as in the case of ironless cored coils, the lines of force produced would be exactly proportional to the current, and in this case—

$$L \times \text{current} = \frac{\text{interlinking of lines and turns}}{10^8}$$

With iron cores, this, of course, is not quite true, but it is often assumed to be sufficiently near for practical purposes. Whether the result obtained will be too great or too small will depend on the part of the magnetization curve we happen to be brought to by the particular current we are dealing with. It should be remembered that the permeabilty is usually fairly high with a current of 1 amp., in a large coil of many turns, and this may be increased or decreased by an increase in current; that depending on the ampere turns produced by the current.

The back electromotive force induced depends on the rate of change of the interlinking. In one second, the field may be reversed by the alternating current a great many times. In many cases of traction alternators, the number of complete cycles is 25, while with machines for lighting the figure varies from 50 to 100. The number of complete cycles per second is called the periodicity or frequency, and is often symbolized by "n" or "~."

The rate of change of the interlinking is equal to $2\pi n$LI, where I symbolizes the current in amperes when alternating. Therefore the back electromotive force induced in the circuit tending to reduce the current that would otherwise flow is = $2\pi n$LI. This is known as the "reactance voltage," while the value $2\pi n$L is called the "reactance."

The electromotive force impressed on the circuit may therefore be supposed to be made up of two components, as shown in Fig. 31: (1) That required to urge a current through the resistance = R × I; and (2) that required to overcome the back electromotive force = $2\pi n$L × I. Now, the one component leads to an

[redacted]

absorption of power in the circuit which shows itself in the heat produced, and is in phase with the current, while the other is 90° out of phase with the current, and does not lead to an absorption of energy, for the energy stored up in the magnetic field while it is being produced is given out again when the circuit is demagnetizing.

If we assume a sine curve throughout our consideration of alternating currents—which is the usual practice—a revolving vector can be made to indicate by its position during a revolution all the phases of an alternating current; thus in Fig. 19 the sine wave to the right was plotted by taking a number of different positions for the conductor, and projecting them on to a vertical line. The altitude then gave values of electromotive force proportional to the sine of the angle of rotation, and by plotting these in extended form to any even scale, we obtained points which enabled us to draw the sine curve.

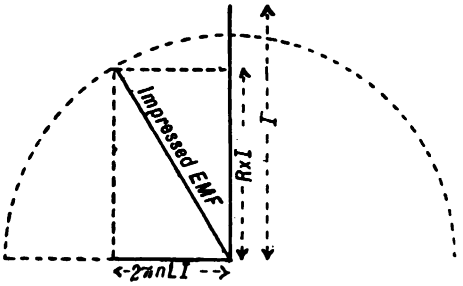

FIG. 31.

In Fig. 32 is shown a vector, OA, supposed to be revolving in the manner described above. The projection of this on to the vertical will represent the value of the electromotive force at any point in the cycle. The second vector, OB, represents the current, which, owing to the inductance of the circuit, is lagging behind the electromotive force through the angle θ. Consider the time when the electromotive force vector has reached its maximum value, the vector OB will not have reached its maximum value at the same time, and by the time the current vector has reached its maximum value, the electromotive force will have declined a certain amount. The power at any instant is obtained by multiplying together the electromotive force, and that com-

[redacted]

ponent of the current in phase with it, or *vice versâ* : for instance, in Fig. 32 the power is equal to OA × OC, for OC is the component of OB in phase with OA; the other component of OB is OD, which represents the magnetizing component, and which does not lead to loss of power directly, though giving rise to the angle of lag. The component OC is equal to OB, multiplied by the cosine of the angle of lag COB, and therefore the power is equal to OA × OB × cos θ, or—

$$\text{Power} = \text{E.M.F.} \times \text{current} \times \cos\theta$$

"Cosine θ" is the power factor spoken of previously, and the above is true, whether we consider maximum values or effective values of electromotive force and current.

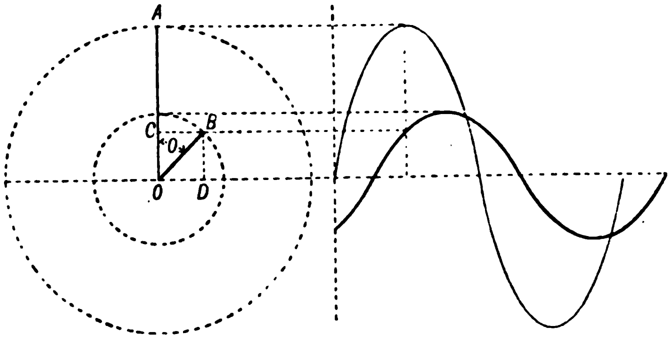

FIG. 32.

In drawing these vector diagrams, any scale may be used for either current or electromotive force, but if there be more than one current or electromotive force under consideration, the same scale must be applied to each.

We have seen that the impressed electromotive force can be considered as made up of two components: (1) The R × I component, or, as it is often called, the "power" component; and (2) the back electromotive force or magnetization component, sometimes spoken of as the "wattless" component, owing to its absorbing no power. The impressed electromotive force, being the resultant of these two, is equal to the square root of the sum of their squares, or—

$$\begin{aligned}\text{Impressed E.M.F.} &= \sqrt{(\text{RI})^2 + (2\pi n\text{LI})^2} \\ &= \text{I}\sqrt{\text{R}^2 + (2\pi n\text{L})^2}\end{aligned}$$

[redacted]

The value $\sqrt{R^2 \times (2\pi n L)^2}$, being that which impedes the flow of a current in an alternating current circuit, is called the "impedance." The value $2\pi n L$ is that part of the impedance which reacts on the circuit, giving rise to a back electromotive force when a current flows, and for this reason it is spoken of as the reactance of the circuit.

The impressed E.M.F. = current × impedance

= current × $\sqrt{\text{resistance}^2 + \text{reactance}^2}$

From this it follows that—

$$\text{The current } I = \frac{\text{impressed E.M.F.}}{\text{impedance}} = \frac{\text{impressed E.M.F.}}{\sqrt{R^2 + (2\pi n L)^2}}$$

It will be seen that, if the resistance of any circuit be very large, compared with the reactance, the latter may be neglected, in which case we have Ohm's law as in direct current work, where $I = \frac{E}{R}$. There is very little reactance in an incandescent lamp circuit, so that such a circuit is usually spoken of as "non-inductive," and leads to practically no angle of lag. Ohm's law in its simple form applies to all such circuits. Again, where the resistance of the circuit is very small, while the reactance is very large, as for instance, a circuit made up of a large electro magnet, wound with thick wire of many turns, the current that flows is very nearly equal to that given by the equation—

$$I = \frac{E}{2\pi n L}$$

It will be seen that if we neglect all but the reactance, we should have a current flowing in the circuit with absolutely no power absorbed in it, and such, of course, is impossible.

Consider a circuit consisting of a large electro magnet as mentioned above, having a resistance of 0·2 ohm, connected to mains at 100 volts, with a periodicity of 60 cycles per second, and suppose a current of 0·5 amp. flows, then—

$$I = \frac{E}{\sqrt{R^2 + (2\pi n L)^2}}$$

$$\text{therefore } 0{\cdot}5 = \frac{100}{\sqrt{0{\cdot}2^2 + (2\pi \times 60 \times L)^2}}$$

$$\text{therefore } 0{\cdot}25 = \frac{10{,}000}{0{\cdot}04 + 39{\cdot}4 \times 3600 \times L^2}$$
$$\text{therefore } 0{\cdot}01 + 35{,}460L^2 = 10{,}000$$
$$\text{therefore } L^2 = 0{\cdot}28$$
$$\text{,,} \quad L = \sqrt{0{\cdot}28} = 0{\cdot}53 \text{ henry}$$

The inductance of the circuit is, therefore, such that the interlinkings of lines and turns by one ampere = $0{\cdot}53 \times 10^8$.

Now, apparently the power absorbed by the circuit is equal to 100 volts × 0·5 amp. = 50 watts, but actually the true power will be very much less, as no allowance is made for the power factor of the circuit, which in this case will be very low. The true power absorbed by the coil will be equal to $C^2R = 0{\cdot}5^2 \times 0{\cdot}2 = 0{\cdot}05$ watt, while a certain number of watts will also be absorbed by the iron, as we shall see later. Putting the latter for purposes of illustration at 10 watts, we have, *true* power absorbed = 10·05 watts, *apparent* power absorbed = 50 watts. The true power is equal to $E \times I \times \cos\theta$, while the apparent power is equal to $E \times I$. If we therefore divide the true power by the apparent power, we obtain the power factor of the circuit. In the above case the power factor $= \frac{10{\cdot}05}{50} = 0{\cdot}2$, *i.e.* the cosine of the angle of lag = 0·2, therefore the angle of lag of the current behind the electromotive force = 78°.

It will be noticed in the above case that the resistance, being small, has very little effect compared with the inductance, which is here very large, and is practically the determining factor in regard to the current. If the coil be unwound, and the wire stretched out straight, the resistance will be the same, but now its inductance will have practically disappeared, and the current will rise to a value equal to $\frac{E}{R} = \frac{100}{0{\cdot}2} = 500$ amperes, instead of 0·5 as before.

Other things being the same, the inductance is proportional to the square of the turns (assuming constant permeability), for with twice the number of turns we get twice the ampere turns per ampere, and therefore twice the flux. But the doubled flux interlinks with double the turns, and therefore the interlinking of lines and turns is four times greater.

In many cases the circuit contains a number of inductances in

[redacted]

series, as for instance, the separate coils in an alternator armature. In this case the coils are similar in every respect, and the inductance of the whole in series, and the impedance of the circuit, is equal to that of one multiplied by the number. Where they are not alike, either in resistance or inductance, the total impedance is the resultant of the two, or more, taken separately, as shown in Fig. 33.

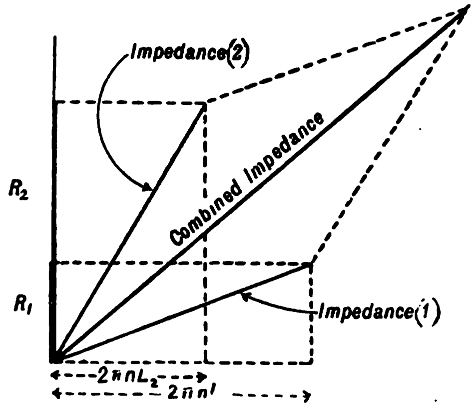

FIG. 33.

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CHAPTER V

THE ALTERNATING MAGNETIC FIELD

IF an alternating electromotive force be applied to the ends of an electro magnet, a current flows, and the iron becomes magnetized, demagnetized, reversed, and again demagnetized, at each cycle; the phase of the flux lagging by 90° behind the impressed electromotive force, as is shown in Fig. 34. Now, a large mass of iron or steel, when magnetized, tends to retain a certain amount of magnetism after the magnetizing force has been removed. This is known as its retentivity. Hard steel has a fairly high retentivity, while good wrought iron and mild steel have it to a much smaller degree. If we perform the cycle of magnetizing, demagnetizing, reversing, and again demagnetizing, as with a single cycle of alternating current, but slowly and in stages, measuring the magnetization produced at each stage, we should trace out the curves O, A, B, C, D, E, F (Fig 35), while the second, and every subsequent cycle, would trace out the curve F, A, B, C, D, E, F, enclosing a certain area, depending on the retentivity of the iron. This leads to a loss of energy, known

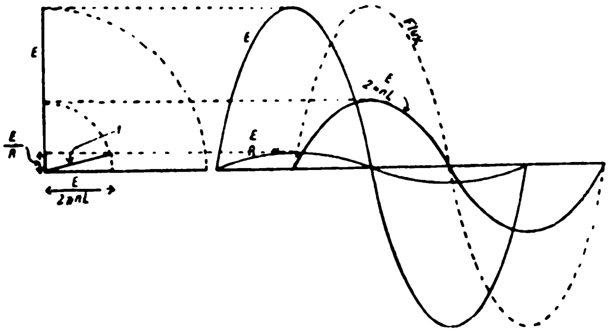

FIG. 34.

[redacted]

as "hysteresis" (lagging behind), for it will be noticed that a certain amount of energy is required to demagnetize the iron before it can be reversed. For instance, the current turns OC are acting in a direction tending to magnetize the core with exactly the same magneto-motive force, both when ascending and descending, and yet, in the one case, they are only competent to take out the residual magnetism, leaving the core unmagnetized, while in the other case they produce a flux, corresponding to the value CG.

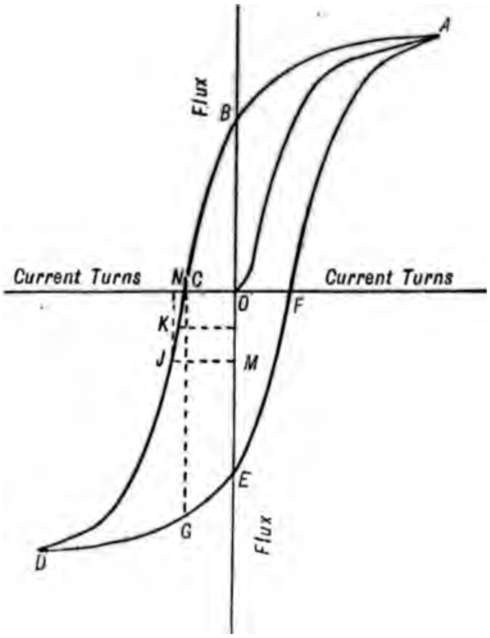

FIG. 35.

The area of this "hysteresis" curve is a measure of the work which has to be done at each cycle in magnetizing and demagnetizing the core. With good magnetic iron, the distance between ascending and descending values is much less than with inferior iron; the loop therefore encloses a much smaller area, even though rising to the same maximum value. If we work at a lower density, the area enclosed will be considerably reduced, and

[redacted]

therefore the work expended in hysteresis will be reduced also. It will be noticed that this hysteresis loss is not brought about directly by magnetizing the core, for the energy put into the circuit in magnetizing it would all be returned to the circuit by the flux in demagnetizing, if it were not for its retentivity.

We have seen that when lines of force are growing in a circuit, an electromotive force is induced in it equal to $\frac{NT}{t}$, N being total flux, T total turns through which they interlink or cut, and t, time in seconds occupied by the cutting. Suppose, having a certain flux corresponding to a certain number of current turns, we increase the current by a very small amount; the current turns will be increased in the same proportion, and the flux will grow to a higher value. As it grows, a back electromotive force is developed $= \frac{NT}{t}$, and power is required to overcome this $= E \times C = \frac{NT}{t} \times C$. The work done is therefore $\frac{NT}{t} \times C \times t$, for work is equal to power multiplied by time. If we express these values in absolute units, then the work done in ergs in increasing the flux is equal to the total lines, N, multiplied by the current turns, CT.

Referring again to Fig. 35, suppose we have a value of current turns equal to OC, then the flux at one part of the cycle is equal to nought. Again, suppose we increase the current by a very small amount, making it equal to ON, the flux will then increase to CJ. The mean value of the flux throughout the change will be CK, assuming that CJ is a straight line, which is more and more the case the smaller the assumed increase in current. The work done in increasing the flux from nought to a value equal to CJ is equal to the increase in flux multiplied by the current turns, *i.e.* equal to OM × HK. This, however, is the area enclosed by CJMO, and therefore this small area is a measure of the work done in ergs for this small increment of the flux. It is obvious that we could do the same for every part of the cycle, and therefore the whole area is equal to the total ergs of work done in taking the iron through one cycle of magnetization.

If we plot values of B, = lines per square centimetre, instead of total flux, then we are only dealing with 1 sq. cm. of the section

[redacted]

of the iron, and if we take as base current turns per centimetre length, we are dealing with only 1 cm. length of the iron, and therefore the area enclosed is the loss in ergs for each *cubic* centimetre of the iron for each cycle.

This amount of energy may seem trifling, but when it is remembered that the cycle is repeated as often as 60 or 100 times in the second in many cases, and that we are often dealing in alternators, not with one cubic centimetre, but with several cubic feet of iron, it will be seen that the energy lost in hysteresis is by no means negligible. With the best quality of iron and steel about half a watt is required for each pound, with a density of 4000 lines per square centimetre, and at a periodicity of 100. At higher densities, the loss will be greater, and not in proportion to the density, for the hysteresis loss is proportional to the 1·6 power of the density. It varies also directly with the frequency, and with the retentivity of the iron or steel, or—

$$\text{Hysteresis loss in ergs per c.cm.} = B^{1\cdot6} \times n \times K$$

(K varying from 0·002 to 0·008, depending on the iron.)

This is a constant loss, and can only be made small by using very good iron or steel, and working at low densities.

Imagine the iron core of the electro magnet to be made of a solid forging. We have seen that the magnetic field springs from the conductors carrying the current, and diffuses through the iron core. In doing so the lines of force necessarily cut through the iron, and therefore induce in it an electromotive force; the same thing taking place as the field disappears. Currents will therefore surge round the solid iron core, first in one direction, and then in the reverse, in such a manner as to oppose any change in its magnetic condition. The electromotive force so induced is, as a rule, fairly small, but the resistance of such a mass of iron is very small indeed, consequently the currents that surge round in this way might often reach to a very high value, and in a short time make the iron exceedingly hot, especially with a high density and periodicity, besides wasting the energy thus going to heat the core. These currents are known as "eddy" currents, and are proportional to $B^2 \times n^2 \times t^2$, where t represents the thickness of the iron, n and B being the periodicity × the magnetic density as before. If we use a *very thin* plate of iron in a plane parallel with the direction of the flux, the eddy currents

[redacted]

in it will be very small, for this will be cut by but a few lines of force, and consequently the electromotive force induced in it will be correspondingly small. Moreover, its length being the same as before, while its sectional area is very considerably reduced, its electrical resistance will be very much greater than before. But seeing that we usually require a fairly large sectional area of iron, a single thin plate seems out of the question. There is no reason, however, why we should not build up the required sectional area of a large number of very thin plates, each one insulated from the next by some light insulation, the eddy currents will then be reduced to a very small amount throughout the whole of the core. The plates are usually shellac-varnished on one face only, and then baked. This is found to be ample insulation between the plates, for the electromotive force induced in any one plate is very small. The effect of thus laminating the iron is shown in Fig. 36, and the more laminations we make, the smaller does the eddy current become. In dynamo work the plates are frequently about 0·013 inch in thickness, and the loss due to eddy currents forms a very small proportion of the total losses.

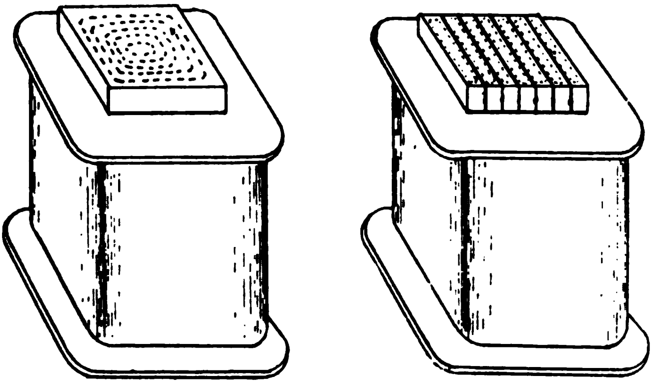

FIG. 36.

It will be understood that with electro magnets in direct current work, there are no eddy currents induced, except at the time of starting and stopping the current, *i.e.* when the field is growing or disappearing, and, of course, this is of no consequence

[redacted]

when maintained for such short intervals. In such cases there is no advantage in laminating the iron—in fact, there is a distinct disadvantage, for the space occupied by the shellac has a permeability of unity, and consequently for any given section of iron we require a larger sectional area of core, and a longer length of wire for a given number of turns. The thin skin of shellac may seem almost negligible taken singly, but with the laminations extending to 1000 plates or more, it forms quite an appreciable proportion of the total sectional area. This is one reason why even thinner plates are not used, for by reducing the thickness to half, the eddy current loss would be still further reduced to quarter its previous value. It will be understood that no amount of subdividing will prevent, or even diminish, the loss due to hysteresis, for this depends on the amount of iron we have undergoing magnetic reversals, and subdividing the core in no way reduces the amount of iron required.

The field-magnet systems of all dynamos are excited by direct current, and therefore in them hysteresis and eddy currents are practically absent, except perhaps on the polar face, as we shall see later. There is, however, one important effect obtainable, which, if ignored, may lead to serious breakdowns. When fully excited, the coil, often of a great many turns, is interlinked with a very large number of lines of force. As this field has been but slowly established, no effects of any importance have occurred; but if, for any reason, the field circuit be suddenly opened—in switching off the machine, for instance—a very high electromotive force would be induced in it, rising often to several thousand volts, due to the cutting of lines and turns as the field disappears. This may be competent to cause a breakdown in the insulation, rendering the machine temporarily out of service. To obviate this, the field circuit should only be opened slowly through a resistance which will cut down the exciting ampere turns in small stages.

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CHAPTER VI

THE CAPACITY OF THE CIRCUIT

THE capacity of the circuit is often of very great importance with alternating currents, and leads to effects opposed to those produced by the inductance of the circuit. Every circuit has more or less capacity, and in special cases the capacity is increased by the addition of condensers, which may be adjusted to raise the power factor in cases where it is low, due to a large inductance in the circuit. This is possible, owing to the fact that a capacity gives rise to an angle of *lead* in the current instead of an angle of lag, as produced by an inductance.

A pair of cables running side by side for a long distance will form a condenser, and, though on open circuit at the far end, will take a current from the alternator, sometimes of fair magnitude; the current being very considerably out of phase with, and in advance of, the electromotive force. The actual amount of true power taken in this way is therefore usually small, but the apparent power is often very large indeed. As the load comes on, the inductance of the circuit, being opposite in its effects, more or less neutralizes the capacity, and the power factor may thereby be raised.

A direct current is proportional to the rate of flow, and is therefore equal to the quantity passing in the unit of time. With an alternating circuit, the current is expressed as the rate of change of the quantity, and is therefore equal to $2\pi n$Q, $2\pi n$ being the rate of change for a sine curve. But the quantity that goes to charge up the cables or condenser is equal to the pressure E × capacity, in a similar manner to the quantity of gas going to charge a gas cylinder. A condenser is said to have unit capacity when unit quantity (1 coulomb) flows in under a pressure of 1 volt. Such a unit capacity is called a "farad."

As Q is equal to E × C, the condenser current may be written $I_c = 2\pi n CE$, C being the capacity in farads, and E the pressure in volts. In any given circuit the capacity will be fixed, and therefore the capacity current will be directly proportional to the pressure.

Take, for instance, the case of an alternator generating a pressure of, say, 10,000 volts, connected to mains running to a substation some miles distant. With the mains on open circuit at the substation end, the current flowing into and out of the cables to charge and discharge them may be as much as 2 or 3 amps. This would be apparently a load on the dynamo of 2 × 10,000 = 20,000 watts with the lower figure, or nearly 27 horse-power, though, as a matter of fact, the power taken from the steam-engine would be very little more than that required to run the dynamo before connecting to the cables, owing to the very low power factor of the circuit due to the large angle of lead.

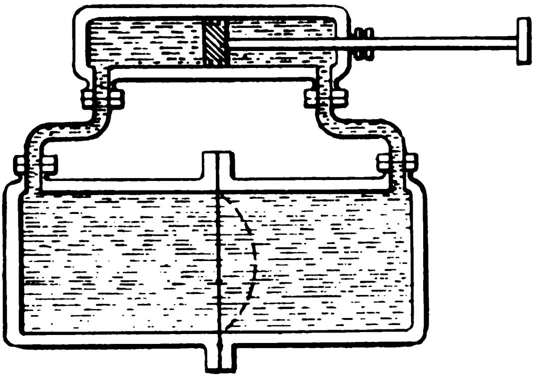

FIG. 37.

An analogy will perhaps make clear the effect of the current being in advance of the electromotive force. Consider Fig. 37. A reciprocating pump in a water circuit supplies an alternating pressure to water. The circuit is not complete, owing to a stout indiarubber membrane being stretched across the larger chamber, dividing it into two compartments. The whole system is supposed to be full of water, and when at rest the pump piston is to be at the centre of its stroke, with equal volumes of water on either side. This represents the electrical case exactly, for, when at rest, there are equal quantities of electricity in the cables or the two sides of the condenser, while the circuit is completely filled

[redacted]

with electricity. There is also no complete circuit, an intervening insulator, which is able to yield without bursting or breaking down under a limited difference of pressure, existing in the insulation of the cables, or the condenser plates.

Imagine the pump-rod to be driven forward to the end of its stroke. A current will start and grow to a maximum value, dying to zero at the end of the stroke, as represented by the curve *oa* in Fig. 38. Water will now have been drawn from the one side and forced into the other side of the condenser, consequently the membrane will be stretched, and will be exerting a back pressure which has grown to a maximum value at the end of the stroke. The pressure difference in the circuit will therefore be represented

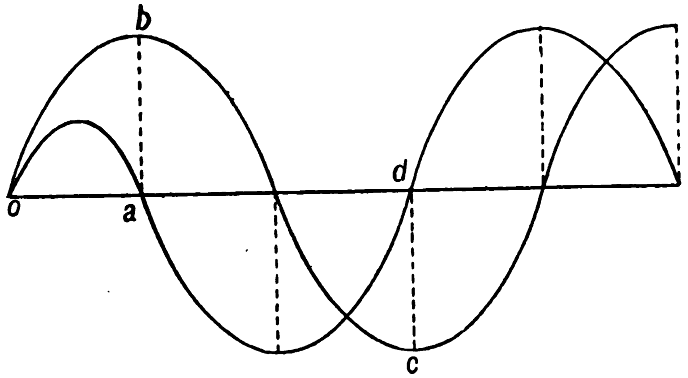

FIG. 38.

by *ob* (Fig. 38). If we now complete another stroke, the current will again rise to a maximum value at the middle of the stroke, and die down to zero at the end, so that the current curve would be represented by *ad* in Fig. 38. The pressure during the stroke will fall from a maximum at the commencement, to zero as the piston reaches the centre, where the membrane will be without stretch, and will then rise to a maximum again at the end of the stroke. This is shown by *bc* in the curve of pressure, and it is evident that this phase relation between current and pressure will continue through any number of strokes.

If these curves are examined in comparison with those given in Fig. 32, it will be seen that they are in exactly opposite phase relation; that is to say, if the current curve in Fig. 32 is supposed

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to be lagging behind the pressure, that in Fig. 38 is leading, the one effect is therefore opposed to the other.

The equation for the condenser current, $I_c = 2\pi n CE$, may be written $I_c = \dfrac{E}{\dfrac{1}{2\pi n C}}$, which makes it more like Ohm's law. The value $\dfrac{1}{2\pi n C}$ is called the condenser impedance, and this we have seen is opposed to the inductive impedance. As every circuit has some resistance, the impedance may have three components: (1) the resistance, (2) the inductance, (3) the capacity component. In the same way the electromotive force or the current may be supposed to have three components: (1) the resistance or power component, (2) the inductance or magnetization component, and (3) the capacity component, as will best be understood by considering the vector diagram (Fig. 39).

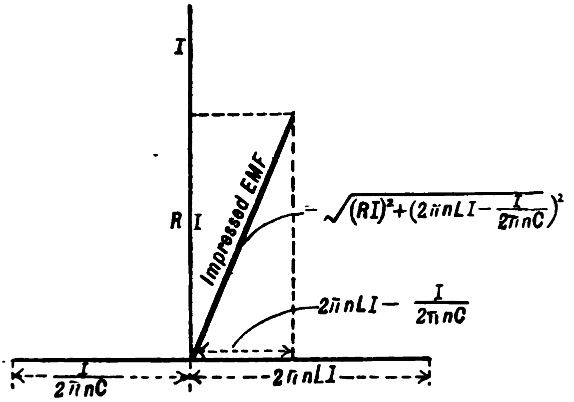

FIG. 39.

Let I be drawn to any scale to represent the value of the current. This multiplied by the resistance of the circuit will give RI, the power component of the electromotive force in phase with the current. The same value of I multiplied by $2\pi nL$ will give the inductance component of the electromotive force at right angles to the current, and again, I multiplied by $\dfrac{1}{2\pi n C}$ gives the capacity component opposed to the inductance component, and therefore 180° out of phase with it. The impressed electromotive force of the circuit is the resultant of the three components, which will be obtained by first deducting the capacity component from the inductance component, or *vice versâ*, according to which is the larger, and then finding the resultant of this and the RI component. The impressed electromotive force can therefore be written—

$$E = \sqrt{(RI)^2 + \left(2\pi n LI - \frac{I}{2\pi n C}\right)^2}$$

$$\text{or } E = I\sqrt{R^2 + \left(2\pi n L - \frac{1}{2\pi n C}\right)^2}$$

We can, however, if more convenient, take components for the current. Thus, in Fig. 40, let E be equal to the impressed electro-

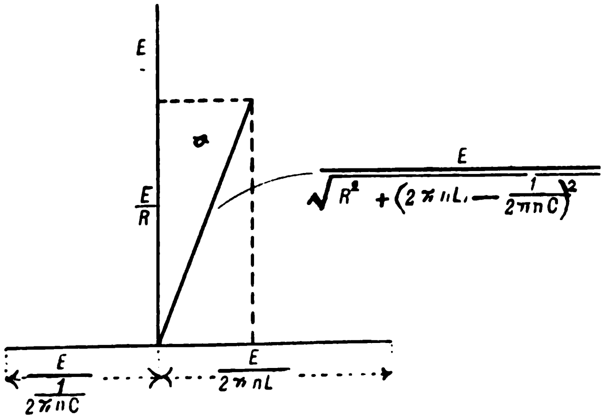

FIG. 40.

motive force. The power component of the current in phase with this will be equal to $\frac{E}{R}$. The inductance component of the current will be equal to $\frac{E}{2\pi n L}$ 90° behind the power component, while the condenser current will be equal to $\frac{E}{\frac{1}{2\pi n C}}$ 90° in advance of the power component. The resultant obtained as before will be equal to—

$$I = \sqrt{\left(\frac{E}{R}\right)^2 + \left(\frac{E}{2\pi nL} - \frac{E}{\frac{1}{2\pi nC}}\right)^2}$$

$$\text{or } I = \frac{E}{\sqrt{R^2 + \left(2\pi nL - \frac{1}{2\pi nC}\right)^2}}$$

When capacities and inductances are in series there is often a great rise in the electromotive force on both, owing to the one charging the other. In this way it is possible for the pressure to rise to so high a value as to break down the insulation. Take the case of a circuit having an inductive resistance of 10 ohms, 0·5 henry, in series with a condenser of 0·00001 farad capacity, impressed E.M.F. = 200 volts, periodicity = 60. The current that

$$\text{flows} = I = \frac{200}{\sqrt{10^2 + \left(6{\cdot}28 \times 60 \times 0{\cdot}5 - \frac{1}{6{\cdot}28 \times 60 \times 0{\cdot}00001}\right)^2}}$$

$= 2{\cdot}66$ amps., and the voltage on the ends of the inductive resistance will be $= v_1 = \sqrt{(RI)^2 + (2\pi nLI)^2} = \sqrt{26{\cdot}6^2 + 500^2} = 500$ volts. The electromotive force on the ends of the condenser will be $= v_2 = \frac{I}{2\pi nC} = \frac{2{\cdot}66}{0{\cdot}00376} = 705$ volts, though the impressed electromotive force is only 200 volts.

The true power in this case will be $= C^2R = 2{\cdot}66^2 \times 10 = 70{\cdot}75$ watts, while the apparent power is $2{\cdot}66 \times 200 = 532$ watts. The power-factor is therefore $\frac{70{\cdot}75}{532} = 0{\cdot}14$, which is the cosine of 82°. This is shown in the vector diagram (Fig. 41).

This great rise in pressure is spoken of as a *resonance* effect. In cases of complete resonance, the rise in pressure is often disastrous, in some cases breaking down the insulation of even the alternator itself. Something has then to be done to change either the inductance or the capacity. But resonance occurs also when inductances and capacities are in parallel. There being a phase difference of 180°, the current is just in the proper relation to pump round from one to the other, and with the slight impulses synchronously received at each half-period, the current sometimes rises to enormous values, the conductors even burning out in extreme cases.

If we take the same inductive resistance and condenser as in the last case and put them in parallel, they must necessarily operate at the same potential difference. There can therefore be no abnormal rise in this respect. We can calculate the separate currents: thus, the condenser current $= 2\pi n \mathrm{CE} = 0{\cdot}653$ amp., while the current in the inductive resistance $= \dfrac{\mathrm{E}}{\sqrt{\mathrm{R}^2 + (2\pi n \mathrm{L})^2}}$ $= 1{\cdot}06$ amps. The latter has two components: (1) that in phase with the electromotive force, or the power component $= \mathrm{I} \times$ cosine of the angle of lag; and (2) the magnetization component lagging by 90°, and $= \mathrm{I} \times$ sine of the angle of lag.

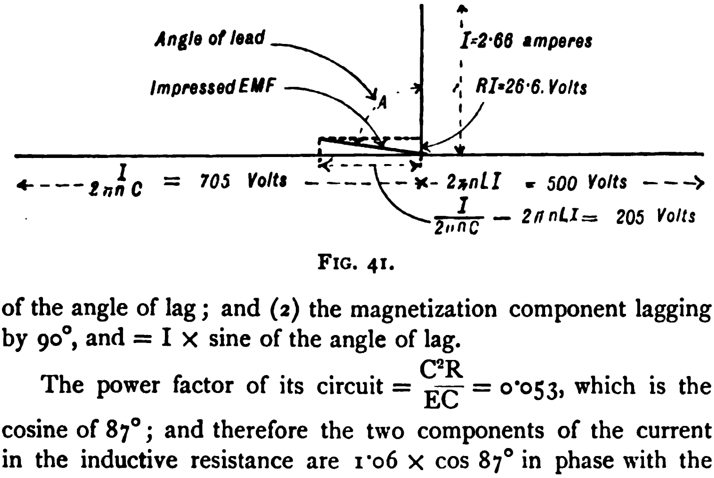

FIG. 41.

The power factor of its circuit $= \dfrac{\mathrm{C}^2\mathrm{R}}{\mathrm{EC}} = 0{\cdot}053$, which is the cosine of 87°; and therefore the two components of the current in the inductive resistance are $1{\cdot}06 \times \cos 87°$ in phase with the electromotive force, and $1{\cdot}06 \times \text{sine } 87°$, 90° behind the electromotive force.

The current in the condenser is 90° in advance of the electromotive force, and will therefore assist in supplying the magnetization component of the current in the inductive resistance. The one can therefore be subtracted from the other, and the dynamo relieved from supplying, to this extent, the wattless energy of the circuit.

The current taken from the dynamo will therefore be $= \mathrm{I}_m = \sqrt{(1{\cdot}06 \times \cos 87°)^2 + (0{\cdot}653 - 1{\cdot}06 \times \sin 87°)^2} = 0{\cdot}407$ amp., which is less than the current in either of the branches taken separately.

CHAPTER VII

BIPOLAR DYNAMO CONSTRUCTION

THE armature conductors of almost all modern, direct-current dynamos are wound in slotted iron cores. The armature core fills most of the space between the pole pieces of the field-magnet system, so that the magnetic reluctance of this part may be reduced to the minimum. The magnetic circuit has, consequently, but two short breaks in it, and the field pole pieces are extended so as to embrace a large portion of the armature core. In this case the armature is the moving element, the field magnets being fixed. In many alternators the arrangement is reversed—the field magnet revolves and the armature is stationary. This is only a matter of convenience. Relative motion of conductors and

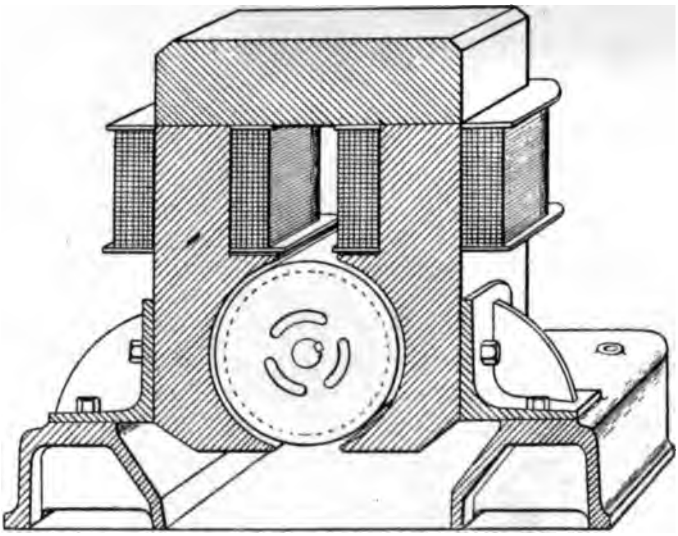

FIG. 42.

field is what is required, and it does not matter in the least which of the two is made into the moving member. In our consideration of direct-current machines we shall start with the smaller sizes, made with two poles only, and consider the larger multipolar machines later. The reason for this is twofold: first, it will probably simplify the subject; and, second, many of the effects obtained in both large and small machines are easier of explanation with a two-pole field, and, if understood in this case, present no difficulties when applied to a multipolar machine.

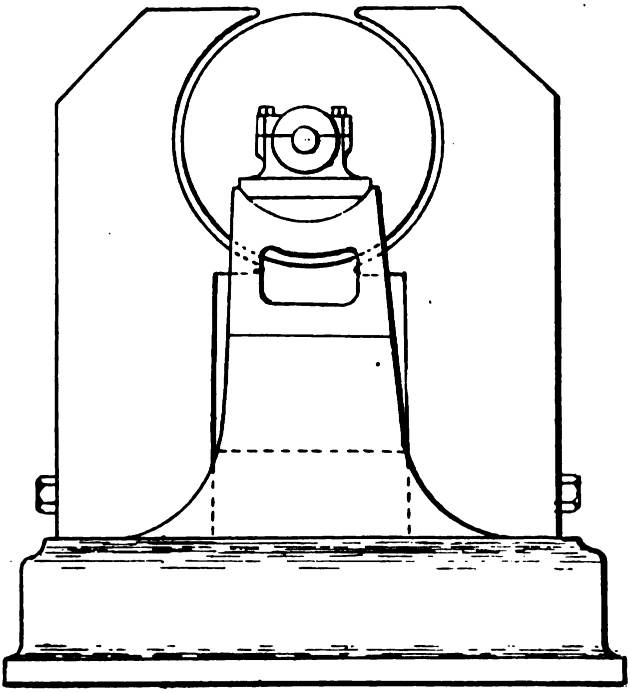

FIG. 43.

Fig. 42 shows the section of a typical two-pole field magnet and armature core, known as the "undertype," from the fact that the armature is arranged under the field-magnet yoke. The advantage of this arrangement is that the bearing pedestals are short; the moving part being low down. For this reason it is preferred for the larger sizes of two-pole machines. When inverted, we have the "overtype" arrangement, shown in Fig. 43, in which the yoke and bedplate are made in the one casting. The chief advantage attending this type is that the magnetic leakage is less than in the undertype, for with the latter, owing to the proximity of the bedplate, a fairly large number of lines of force cross the gaps and complete their circuit through it, rather than by the armature core.

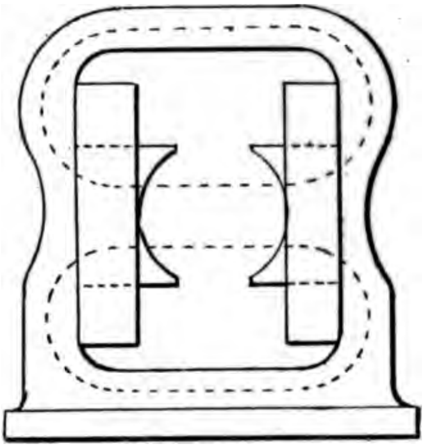

FIG. 44.

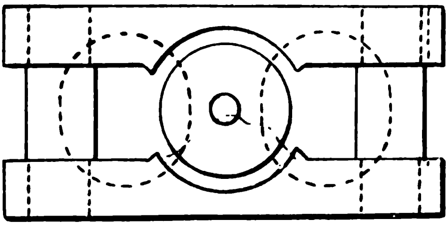

FIG. 45.

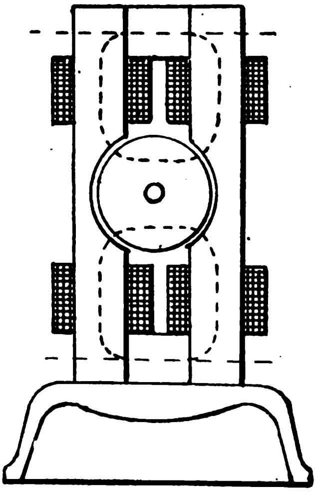

FIG. 46.

There are many other arrangements of two-pole fields, but they are not used to any great extent. A few are shown in Figs. 44–46, as they typify cases of simple divided magnetic circuits, the path of the lines being indicated by dotted lines in each case.

In Fig. 42 the field magnet is supported by gun-metal or brass brackets, which have to be very massive to hold perfectly rigid such a heavy mass of metal and the exciting coils. Some non-magnetic metal is absolutely necessary for these brackets, for, if

[redacted]

made of iron or steel, the magnetic leakage through them would be very great indeed. For the same reason the space between the field-magnet pole pieces and the bedplate must not be too short, for it must be remembered that two short air gaps are absolutely necessary in the main field circuit, across the armature; and the flux will divide between this path and the alternative path through the bedplate in inverse proportion to their respective reluctances.

In Fig. 44 the field-magnet limbs are usually made of wrought iron or steel, while the double yoke is of cast iron. The cores may be cast in with the yoke, but are often bolted on separately, after the surfaces have been carefully planed and scraped.

The pole-pieces in Fig. 45 are usually castings, the bottom piece being one with the bedplate. The field cores, circular in section, are usually of wrought iron or steel, and are turned at the ends to fit into holes in the castings. This ensures a large surface of contact between the two, and, consequently, a low reluctance joint. The field-magnet system of Fig. 46 is usually built entirely of wrought iron or steel, except for the bottom yoke, which is cast into the bedplate, and serves to support the whole.

The sole object of the field-magnet system is to magnetize the iron core of the armature, and the more directly it does so the better. The limbs should not be unnecessarily long, and the magnetomotive force, exciting the magnetic flux in the whole circuit, should be brought as close up to the armature as possible. In this respect the design shown in Fig. 44 would appear to be superior.

It is to be remembered that all joints in the magnetic circuit should be carefully surfaced up, for if left roughly planed the parts are in contact at a few points only, and the reluctance of the small air gaps thus formed will often necessitate as many additional ampere turns as would be caused by several inches additional length in the iron. The best field-magnet system, from a magnetic point of view, would be one made in a single forging, with the corners well rounded off; but this is practically never met with, owing to the difficulties and expense of manufacture. Where joints occur the parts have to be fixed together with massive steel bolts, for they have to withstand not only the ordinary strains due to the weight, but also the magnetic pull of the armature, which in large machines is very considerable. There must be absolutely no yielding of the field cores under these stresses, for the length of the air gap is, in many cases, not much more than a mechanical clearance; and it is essential that it be kept symmetrical in every case. Of course, there is a very large magnetic pull between the field cores and the yoke, tending to counteract the pull on the pole-pieces due to the armature; but the latter acts with much greater leverage than the former, and is therefore much more effective.

The angle formed by joining the pole tips to the centre varies but slightly in all bipolar machines, being usually somewhere about 120° or 125°. If the angle be much smaller, the commutating field becomes excessively weak, as will be explained in the next chapter, while if much larger there is an abnormal amount of magnetic leakage from tip to tip.

The armature core is in every case built up of laminated iron or steel, for in sweeping through the field an electromotive force is induced in it, which would cause large eddy currents to circulate if it were solid, thus heating the core and wasting energy, for the eddy currents induced tend to oppose that which produces them, and therefore oppose the motion—*i.e.* they tend to drive the armature in the reverse direction, and thus form a magnetic brake (see p. 62).

There are two distinct types of armature, known as "ring" and "drum." In the former the laminations are made of ring-shaped stampings of thin sheet steel, or iron, with slots in the outer edge to take the conductors, and three or four wider ones equally spaced in the inner edge to fix them to a driving spider. Fig. 47 shows a ring armature core. The drum armature core is built up of discs, which are fixed to the driving shaft by one or more keys. Holes are usually punched in the discs, so that when built up to the required thickness on the shaft, tunnels are formed which allow air to circulate through them. This type of core is shown in Fig. 42.

The slots are usually punched out by special presses, a few at a time, and any burrs formed in the process are removed by emery wheels. In some cases the slots are punched slightly smaller than required, and after the core is built up they are milled out. This leaves them smooth and clean, but is more expensive, and there is the possibility of burring the plates, which tends to increase the eddy current loss.

On the whole, it is perhaps best not to tool them in any way after being built up, but to get them into line by building up on a sufficient number of guide-rods. The shape of the slots varies considerably. Some are formed with parallel sides and open ends, as shown in Fig. 48, the ends being notched in some cases to allow of wooden wedges being driven in to support the winding against centrifugal action, as represented in Fig. 79, and these have distinct advantages. If wound by hand the conductors are easily fixed, and there is not much fear of injuring the insulation on the wire in winding. They also allow of coils being wound on special formers, which, after being carefully insulated, may be dropped, or pushed, into the slots. This method, applicable only to drum armatures, often saves time, and allows of an injured coil being replaced by a new one with a minimum of time and labour. The coils, however, have no support with open slots against their tendency to fly out under the centrifugal force created as they

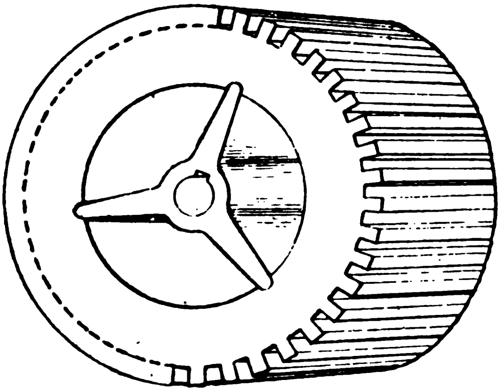

FIG. 47.

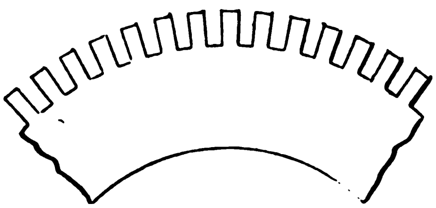

FIG. 48.

[redacted]

revolve, and therefore have to be bound down with steel wire, wound on top of a protecting thin coating of mica and strip brass, otherwise they would bulge outwards, and soon be injured by coming into contact with the pole pieces. There is the further disadvantage attending wide open slots that the magnetic flux crosses the air gap in a series of tufts, each of which is drawn by the teeth in the direction of rotation for a short distance before springing to the next tooth, and this swinging of the flux across the surface of the pole pieces induces eddy currents in them, leading to heat and waste energy. To minimize this the width of the slots should not be greater than twice the length of the air gap, for with short air gaps the eddy current loss in the pole pieces produced in this way rises rapidly. Laminating the pole faces will, of course, prevent eddy currents, but this is more easily accomplished in multipolar than in two-pole machines, where each pole face spans an arc of about 125°.

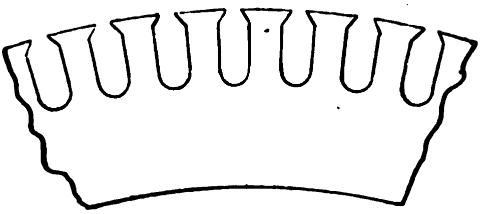

FIG. 49.

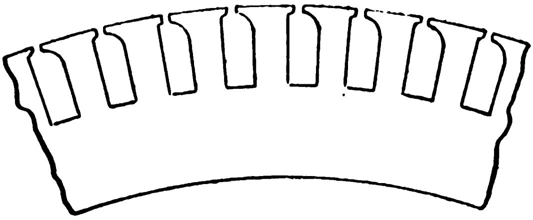

FIG. 50.

With partially closed slots the conductors are better supported against centrifugal action, and there is much less shifting of the field on the polar face. Figs. 49 and 50 show forms of slots which are partially closed at the top. These, of course, exclude the use of former wound coils, and the slots are not so easily cleaned out and insulated as open slots.

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The depth of the slots is a point of great importance, affecting considerably the performance of the machine when completed. For a reason which will be explained when considering the commutation of the current, the smaller the depth the better, but with shallow slots we should require a much greater number to get any given number of conductors in, and this would necessitate cutting away more iron, leaving very thin teeth. These would be saturated with a relatively few lines, and consequently the reluctance, down to a point below the bottom of the slots, would be excessively high, so that a compromise has to be made. Very good results are obtained with a depth of slot not greater than 2·5 or three times the width, while the width of tooth and slot is alike in many cases, though with parallel-sided slots the teeth are slightly smaller in section at the root than at the outer edge.

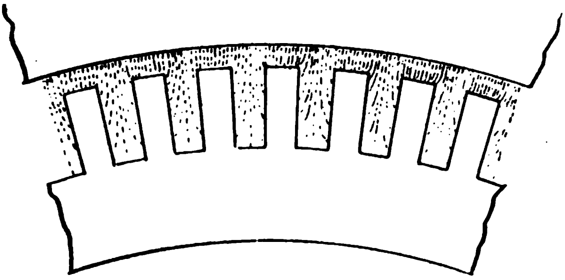

FIG. 51.

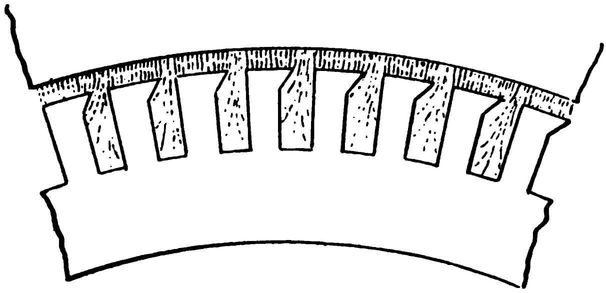

FIG. 52.

The magnetic density in the teeth will in many cases be fairly high, and their reluctance therefore rather high. The flux divides between teeth and slots inversely proportional to their reluctances. The distribution in teeth and slots will be as shown in Figs. 51

and 52, while undisturbed by the magnetic field created by the armature current, known as "armature reaction."

The plates, after punching, are usually coated on one side only with shellac varnish, and dried in an oven. A stout cast-iron end-plate bears against a collar on the shaft, which is supported in a vertical position, and the plates are threaded on, one at a time, with the shellaced surface of each in the same direction, till a depth of three or four inches is obtained. The first two or three plates are usually made thicker than the others, for the teeth have no support at the ends, and unless made stiffer they tend to spread over the cast-iron end-plates.

Some makers cut the plates gradually smaller at both ends for about three-quarters of an inch, till they round off to the bottom of the slots, but this necessitates special machine tools for cutting them, with a screw adjustment to graduate the diameter. The number of sharp corners formed by this practice is also rather apt to injure the insulation unless great care be taken in winding.

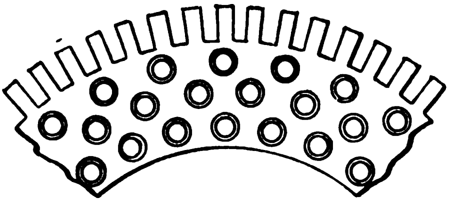

FIG. 53.

A ventilating space is now made, and the building-up process continued for another three or four inches. These ventilating spaces are formed in a variety of ways. In some a disc of the same size, but considerably thicker, with the surface pressed in both directions into a series of saucer-shaped indentions, and with the teeth twisted through 90° to their normal position, are employed (Fig. 53). One of these coming between a series of dics will provide a large number of paths through which air may circulate and assist in keeping the iron cool. In another method strips of sheet-steel are inserted on edge, and are kept in position by small tongue pieces punched in one of the plates (Fig. 54). In other cases a few broad fibre strips are employed (Fig. 55), but these cannot be placed higher than the bottom of the slots, and

[redacted]

therefore form no support for the teeth; while in another case small hard wood blocks of the required thickness are evenly spaced over the plate at the place where the ventilating space is required. A method which gives support right to the top of the teeth is to be preferred, for without it the teeth on both sides fall over considerably, and close up the space more or less.

In building up the core a number of plates slightly smaller in diameter are threaded on at intervals to allow space for the binding wire, unless the conductors are to be clamped in the slots by wooden wedges driven into the notched teeth.

The peripheral speed of the armature is usually high, so that the centrifugal force tending to throw the conductors out of the slots is fairly large. The breaking strain of the steel piano wire used for binding is about 45 tons per square inch, so that a single number 16 S.W.G. wire will break with a strain of about 300 pounds.

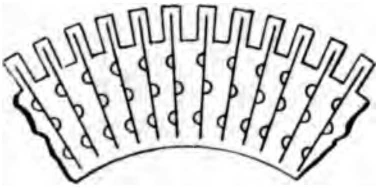

FIG. 54.

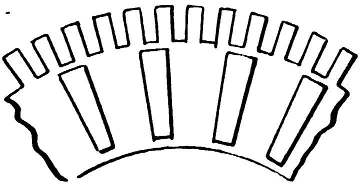

FIG. 55.

The centrifugal force on each conductor or on the whole of the winding is equal to—

$$\text{C.F. in lbs.} = \frac{\text{weight of winding in lbs.} \times (\text{velocity in ft. per sec.})^2}{32 \times \text{radius of armature in ft.}}$$

$$= \frac{\text{weight in lbs.} \times \left(\dfrac{2\pi r \times \text{revs. per min.}}{60}\right)^2}{32 \times r}$$

$$= \frac{\text{weight in lbs.} \times 4\pi^2 r^2 \times \text{revs. per min.}^2}{32 \times r \times 3600}$$

$$= (\text{weight in lbs.}) \times (\text{revs. per min.})^2 \times (\text{radius of armature}) \times 0{\cdot}00034$$

There should be, of course, a very large factor of safety on the binding wire where such is used. Wooden wedges driven into notches punched into the ends of the teeth form perhaps the best support, for small eddy currents are apt to be developed in the binding wires, owing to them being soldered together on top of the thin brass strip, and it sometimes happens that the soldering gives way under the centrifugal action and the slight softening of the solder, a risk altogether avoided with the wooden-wedge method.

When the required number of plates has been threaded on in the above manner, a second thick end plate is put on, and the whole clamped firmly together with nuts screwed on to the shaft. These thick end plates are usually provided with a deep flange projecting from the upper edge, to form a support for the end connections of the armature winding, and are often pierced with holes all round to preserve the ventilation of winding and core, as shown in Fig. 56.

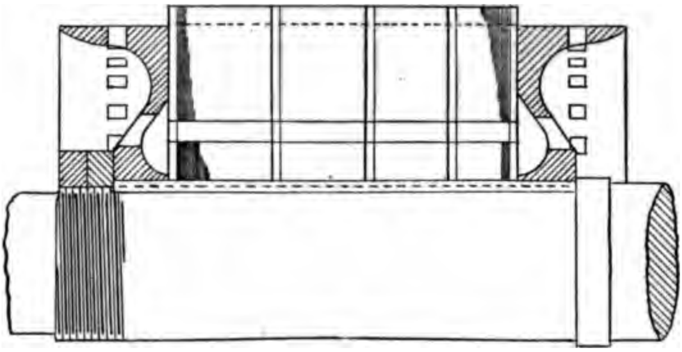
FIG. 56.

With a ring winding, the same process is followed, except that the gun-metal spider is first keyed to the shaft, and the building up process is then done on the spider arms, which are provided at one end with radial projections reaching to the top of the laminations, and forming the end support for them. After the last end plate is put on, a three-armed gun-metal washer is pressed hard against them by nuts, as in the case of the drum armature. The spider and end washer are shown in Fig. 57.

Ring armatures are usually made shorter than the drum type, on account of the amount of idle wire required as series connectors with them, as compared with the drum. In the ring type a conductor lying in one of the slots is connected to the next one

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to it, in series, by continuing the wire radially down one face, through the inner space between the spider arms, and up again at the other end.

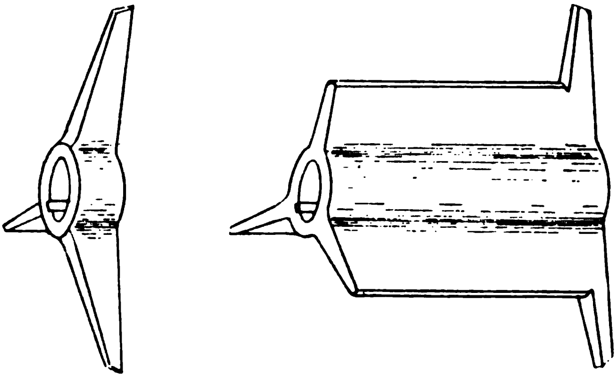

Fig. 57.

After first finding the total number of conductors to be wound in the slots, by a method to be explained later, they are divided up into about sixty coils of one, two, three or more turns each, as the case may be, and each little coil wound on symmetrically in the manner explained above. It will be seen that each conductor in a slot forms one complete turn by the connecting wire which

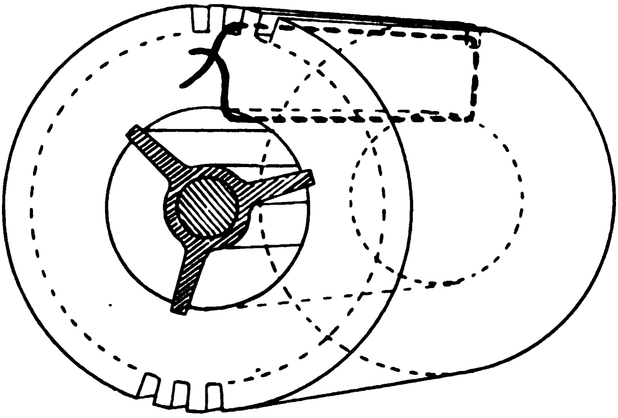

Fig. 58.

puts it in series with the next, as shown diagrammatically in Fig. 58. The length of active conductor in the slots, therefore, forms but a small proportion of the total length of wire to be wound on.

In the case of the drum armature, one conductor in a slot is connected to a second conductor by passing across the end face of the core in one of several methods, and completes one turn by crossing again at the other end (Fig. 59). In this case each turn contains two active conductors and two end connectors, and as the latter are no greater with a long than with a short armature of the same diameter, there is a decided advantage in making it long, for then the active wire forms a larger proportion of the total.

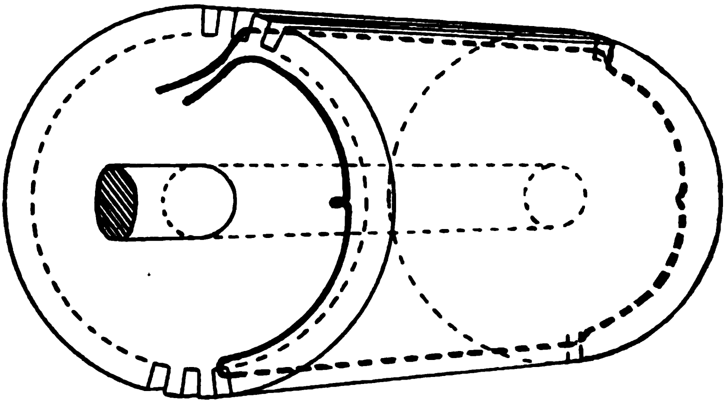

FIG. 59.

The method of winding-drum armatures depends partly on the size of the conductors. With small sizes, the wire is simply bent round the shaft on top of a short insulating tube, which is first slipped over the shaft. The turns, therefore, necessarily overlap, and bulge outwards at both ends (see Fig. 60), which makes this method almost impossible in the larger sizes. It has also the serious drawback that, in the event of a coil being burnt out or injured in any way, it often necessitates a very considerable unwinding of uninjured coils before the damaged one can be removed, owing to the overlapping at the ends.

The commutator, consisting of as many bars as there are coils in the armature winding, is built up on a sleeve as an entirely separate piece from the armature, and keyed or fixed with lock-nuts to the shaft, one, two, or more inches in front of the armature core, depending on the size of the machine. This is the only part of the dynamo, with the exception of the bearings, which is subject to wear, and being made in this way it can be readily disconnected and a new one fixed at any time. It is also the weakest part of the machine, and has to be made with the greatest care in every detail. The bars are usually made of hard-drawn copper (taper in section, Fig. 61), and are insulated from one another with thin mica strips, the whole being insulated from the supports by mica, micanite, or vulcanized fibre rings. The bars slowly wear away, owing to the friction of the brushes, and occasionally have to be turned smooth, so that a certain depth is necessary to allow for this wearing. The amount varies with the size of the commutator, but for two-pole machines seldom exceeds $\frac{5}{8}$ inch. Each bar, after being cut to the required length—including the necessary amount for turning the supporting surfaces at each end—is fitted with a lug piece, to which connection can be made by two of the armature conductors. These lugs are sometimes made of strips of hard-drawn sheet copper, and sometimes cast in gun-metal. With the former, a saw cut is made in the end of each bar, wide enough to take a doubled thickness of the copper strip. The strips are filed so as to fit into the bottom of the saw

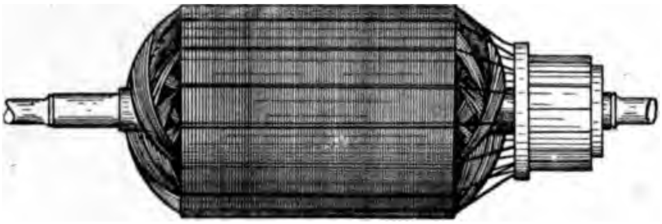
FIG. 60.

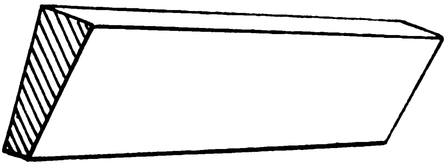
FIG. 61.

[redacted]

cuts, and are riveted, and also soldered in. The other ends are then formed into a receptacle for the wires, in one of the methods shown in Fig. 62. In the last three, the ends are bent round so as to embrace the conductors, and thus secure them against their tendency to fly out, due to centrifugal force. With large conductors, however, it is easier to get them into the first, and it is also considerably easier to solder them with certainty. They can afterwards be bound in to counteract centrifugal action. With cast lugs it is important to make a good mechanical and electrical joint between the casting and the copper segment, either by dovetailing and soldering, as in Fig. 63, or by some equally effective method.

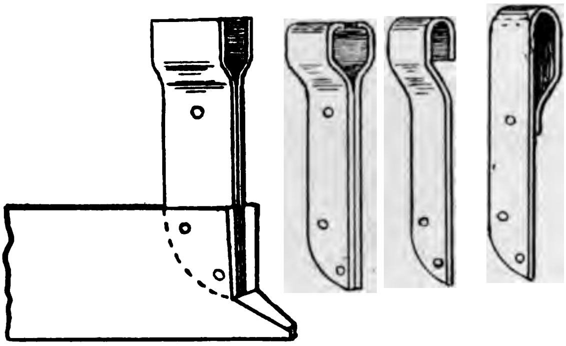

FIG. 62.

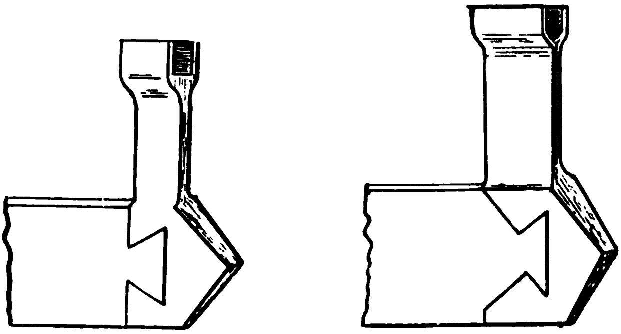

FIG. 63.

After machining, or filing to gauge, the bars, with a strip of

[redacted]

mica between each, are assembled round a mandril, or inside a cast-iron ring, having clamping pieces and bolts, by which a fairly large pressure may be brought to bear. The electromotive force between adjacent commutator bars varies, but is never high; the maximum potential difference existing between bars that are midway between brushes, falling steadily on either side to zero. The thickness of the mica insulation, therefore, need not be great, $\frac{1}{32}$ inch, or thereabout, being sufficient. Pressure is then applied to bring the whole quite firm, so that it should be impossible to get the thin edge of a knife-blade between the segments. If it is found to be loose, it must be taken apart, and a very thin strip of mica cemented on to each bar with shellac. It is absolutely essential that the bars be perfectly rigid, for a loose bar will in a short time lead to breakdown. The vibration caused thereby would probably soon loosen the connection of the conductors. Copper dust would lodge between the segments, and might cause a short circuit in an armature coil, and there would be sparking as the brush passed over, with the formation of a flat surface on the loose bar, and probably on one or more to either side of it, which would increase the sparking trouble, and soon lead to a complete stoppage. To get them perfectly tight, it is essential to work each bar to the exact taper, and to compress the whole with high pressure, for mica is a substance with little or no elasticity.

Some makers put the final pressure on to the commutator with a hydraulic press, formed of a stout ring supporting, radially inwards, eight or more rams, all connected together so as to work simultaneously. The commutator, after being tightened up by hand, is then placed inside the press, and a clamping ring, made in a number of sections, placed round it. The rams then force the sections together with very great pressure, as much as 200 tons in some cases. Clamps are then put round it to hold it firmly until it is turned at the ends to take the final supports.

The method of supporting the commutator on its sleeve varies considerably. Usually the sleeve is of cast iron or steel, and is formed with a mushroom head, as shown in the sections, Figs. 64–67. The rise in the sleeve may be made to any extent, and is provided so as to obtain a larger diameter commutator, and therefore thicker bars with any given number. The centring head (Fig. 65) gives a very good support; but, as in the case of Fig. 64, it takes up a certain amount of space on the shaft, which is avoided in Fig. 67. The thick black lines in each figure represent rings of insulating material, so that each bar is effectively insulated from the sleeve, and at the same time firmly fixed to it by the sleeve head at the one end, and the mushroom-headed washer and locknuts at the other.

The length of the bars is determined by the current to be

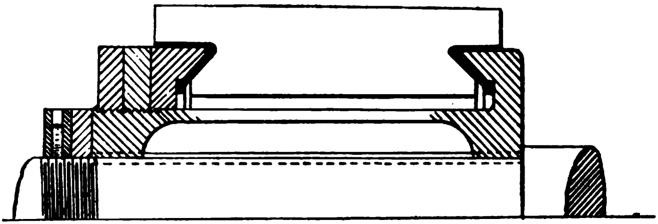

FIG. 64.

collected. After deciding the diameter and number of bars, the width at the surface of each bar is fixed. This width, multiplied by the length of the bar, gives the sectional area through which a certain portion of the total current has to be collected. Now, we cannot allow above a certain current density

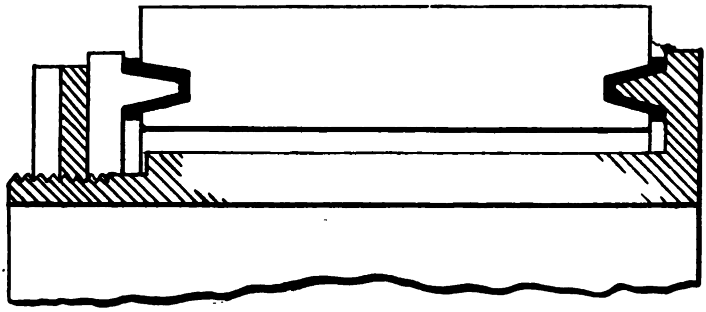

FIG. 65.

in the contact area between commutator surface and brush, depending on the kind of brushes employed, owing to the heat developed and the voltage drop, which would become excessive with high values. With copper brushes this is about 150 amps. per square inch, while with carbon brushes it is rarely more than 35 amps. per square inch, and the latter are now much more commonly employed than the former, for a reason we shall see presently. In deciding the wearing length, notice has also to be taken of the space occupied by the brush-holders, and this has to be added to that required by brush contact.

Some makers turn the commutator on the inside edge, and likewise the whole surface of the sleeve, so that rings of insulating material may be inserted between the two, as shown in Fig. 66. This makes the commutator firm on the sleeve, and more able to resist the displacement of a bar or bars by an accidental blow, or by careless handling. This is a point of some importance in cases where the final pressure in building up is not so great as to preclude the possibility of such an accident; but where great pressure is applied, as, for instance, with the hydraulic press,

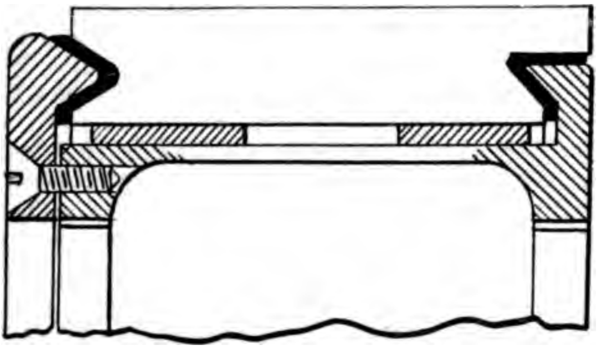

FIG. 66.

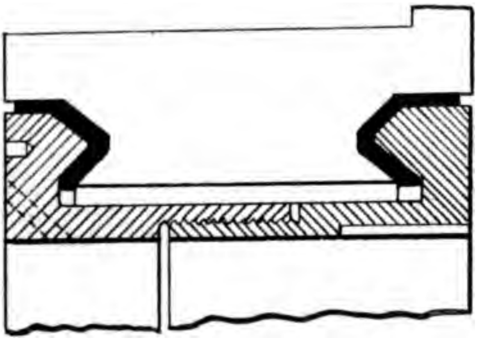

FIG. 67.

an accidental blow of this nature should not produce any displacement. With end supports only, the space between the sleeve and the inside of the commutator bars may be left rough; the only turning necessary being at the bearing surfaces, but these, of course, should be designed to pull up very tight.

Should a bar get displaced for any reason, either by bulging outwards, or by sinking, the effect is to cause the brushes to jump as the bar passes under them. This produces serious sparking, which very soon burns away portions of adjacent bars, forming ruts, which further increases the trouble. In this way the machine soon becomes unworkable, and to rectify it the commutator has to be turned, or ground up true once more. This should be done at the earliest possible opportunity, for if allowed to run for any length of time while sparking in the above manner, the ruts quickly become deeper, necessitating much more turning or grinding to bring it smooth, thus very materially shortening the life of the commutator.

The bars should also be uniform in hardness, for if there be a bar much softer than the rest it will tend to wear more rapidly, and produce a *flat*, which may lead to sparking, due to the cause just mentioned. With the sections made from hard drawn copper, sawn from long lengths, as it is obtained from the rolls, the possibility of having a soft section is almost precluded. It should be remembered, however, that the outer layers are much harder than the inside, and that to file, or machine down a few larger bars to make them serve in building up a smaller-sized commutator may introduce bars not quite uniform in this respect.

It should also be remembered that mica varies very much in hardness, and if the hard varieties are employed it will not wear as fast as the segments, and consequently will soon form a series of ridges, which not only cause considerable noise, but rapidly wear away the brushes, and may cause sparking under load. Soft amber mica is the only kind suitable for this work, as it is found by experience to wear at about the same rate as hard-drawn copper.

The completed commutator may be fixed to the shaft by keys, or by locknuts, as shown in Fig. 64. It is just as essential that there should be no possibility of movement of the commutator as of the armature core, for though the force acting on it is very considerably less, the armature conductors make connection to it by a

[redacted]

series of soldered connections only, which are not mechanically very strong, and slight vibration would soon work them loose. The key-way prevents any possibility of slip, and therefore is perhaps better than locknuts alone, though where these are used a short key, or a grub screw, is usually provided in addition.

The shortest and most direct connection from the armature conductors to the commutator lugs is to be preferred, for all unnecessary length is simply adding to its resistance. In some cases, however, it would be very inconvenient, if not mechanically impossible, to arrange the brushes in their correct position with the connections so made. It then becomes necessary to stagger the connections more or less; thus in Fig. 68, instead of the ends of the armature winding going straight to the commutator bars, they are bent and connected to bars 90° from this position. The brushes in this case will press on the commutator, not in the plane at right angles to the field, but in line with it, though in this

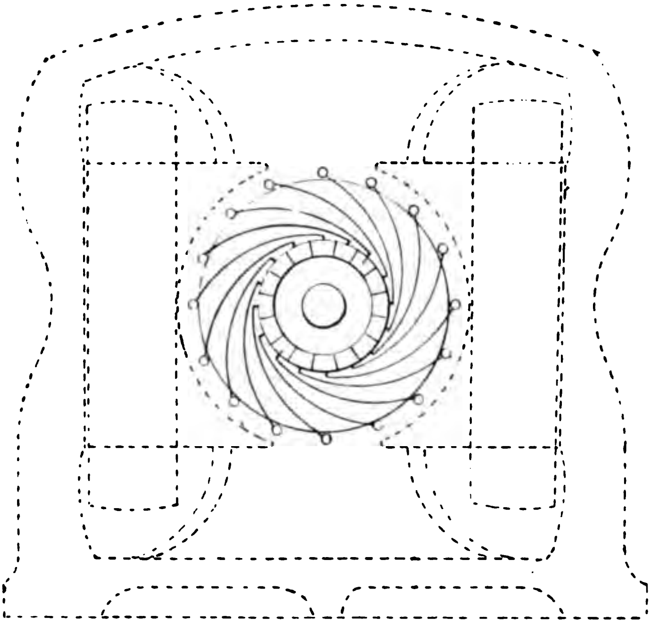

FIG. 68.

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position they are making contact with a coil, whose plane is at right angles to the field.

Carbon brushes are now used in almost every case, owing to their superior commutating properties, as will be explained in the next chapter. With the introduction of carbon brushes a different type of brush-holder was found to be necessary, and a very great variety have been devised. This is, perhaps, not so surprising, for the superior properties depend largely on the holder, and a machine of good design in every other respect may give trouble due to such a small item as a poorly designed brush-holder.

Owing to the much lower current density employed with carbon brushes, a larger contact area is necessary, and the brush usually consists of a block of carbon, supported in one of two ways, so as to press radially on the commutator face. In one type the carbon block is fixed in the holder, the whole being pressed on the commutator by means of an adjustable spring. In the second type the holder is fixed, while the brush is free to move in a box against the action of a spring, which holds it in contact with the commutator. The latter type has the advantage of less inertia, which enables it to respond quicker to any slight irregularity in the surface, but owing to the loose contact in the box, it is necessary to connect the carbon brush by a flexible copper connector to the holder. To reduce the resistance of the brush, the carbons are usually copper plated. Figs. 69 and 70 are illustrations of these two types. The first, made by the Lister Electric Manufacturing Co., consists of a light metal frame, to the end of which the carbon block is clamped by a screw plate. To replace a brush is the work of but a few minutes. It has a hold-off device, with screw adjustment. By pulling the small ball head at the top the holder is released, and the spiral spring pulls the brush into contact with the commutator.

In Fig. 70, known as the " Aston " worm-feed brush-holder, the adjustment is made by a worm and worm wheel, which puts more or less tension on a spring attached to a pressure lever. This lever is tipped with rollers at the points of contact with the brush to minimize the chance of the brush sticking in the box. The flexible copper connector attached to the carbon block is seen at the front.

On the Continent the finger type of brush-holder seems to be

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preferred. Fig. 71 represents one of this type, in which the carbon block is rigidly fixed in the movable holder. With this type the spindle is often facing a point on the commutator which is at a considerably higher potential difference than the brush,

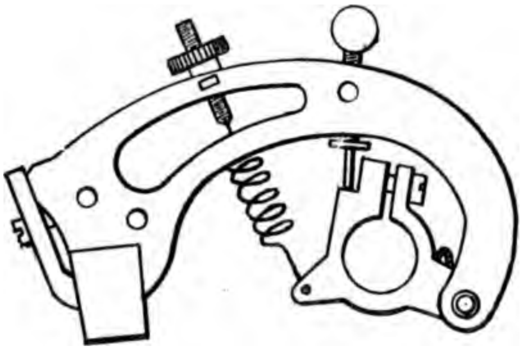

FIG. 69.

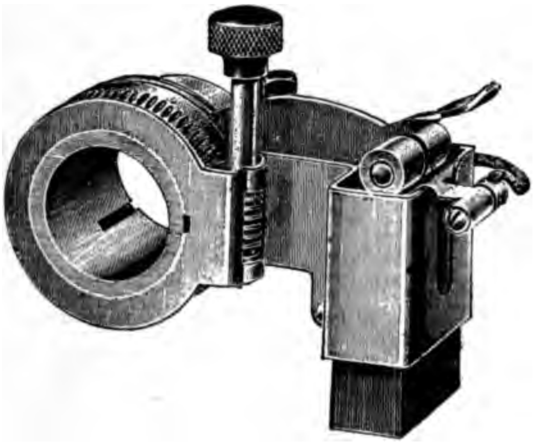

FIG. 70.

and if it be fixed at but a short distance from the commutator face, as is often the case, there is the possibility of sparking across. There is also more chance of vibration than with a short, rigid holder.

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The holders should be as compact as possible, for usually a large number are required on the one spindle, and any waste space due to the brush-holder necessitates a longer, and therefore more expensive, commutator. In some cases the distance between the various brushes scarcely exceeds $\frac{1}{16}$ inch. Perhaps the best in this respect is that known as the "reaction" type of brush-holder. In this the holder is rigidly fixed, but instead of having a box to support the carbon brush, it has but a single flat surface, against which a triangular wedge-shaped carbon block is pressed by means of a spring finger. The carbon is pressed into contact with the commutator by the action of the spring, and the reaction of the brush-holder surface. Fig. 72 shows a reaction type of holder.

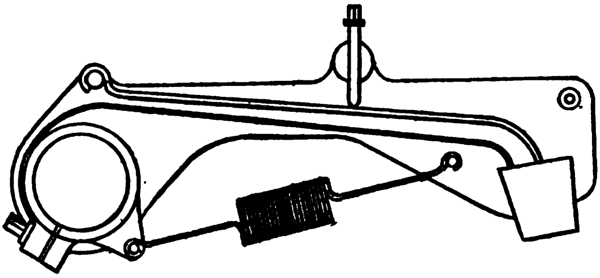

FIG. 71.

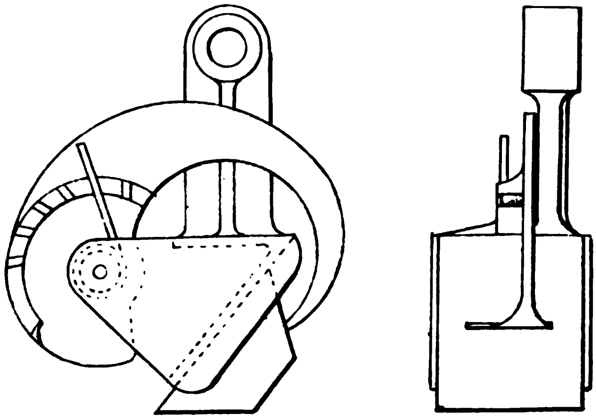

FIG. 72.

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Some makers treat their carbons by boiling them in oil or paraffin wax, which gives a certain amount of lubrication, and minimizes the noise often attending the use of carbon brushes. The hard, coarse variety of carbon seems to give the best results, and after a time the commutator face assumes a bright, polished appearance, in which case the wear is exceedingly slow. In some cases, where the brushes give trouble due to excessive shrieking, or grinding noise, a touch on the commutator of a lubricant consisting of equal parts of plumbago and paraffin wax melted and mixed together, has been found to entirely remove it, but if the commutator face can be made into a bright, polished surface, it is as well not to interfere with it with lubricants of any kind.

We have mentioned two types of winding, viz. ring and drum. Little more need be said about the former (shown diagrammatically in Fig. 28), for, though it has certain advantages, the disadvantages more than counterbalance them, except perhaps in the smallest sizes. The chief disadvantage attending ring winding is the necessity of threading each turn, by hand, through the restricted space in the interior, which is no easy matter with large-size conductors. There is also the possibility of injuring the mechanically weak insulation in so doing, and difficulty is experienced in keeping the winding on the inside perfectly symmetrical. Any uneven distribution of the winding causes a want of balance, with consequent vibration and noise, when running at a high speed. With drum armatures, the coils can be wound on formers, if desired, and taped or otherwise insulated, and bound together, and dropped in their place on the outer face of the armature core. The winding is thus perfectly symmetrical.

It will be noticed that ring winding forms one continuous spiral or coil, with connections from it to the commutator at intervals. The winding is closed on itself, and therefore apparently short-circuited; but if we apply the hand diagram given on p. 38 to determine the direction of the current that would flow under the electromotive forces induced in the two halves of the winding, we find that they are in opposition in so far as the windings themselves are concerned, and therefore no current can flow round them in series, otherwise it would be impossible to have a closed winding at all. The brushes put the two halves in parallel, so that the outside circuit is fed under an electromotive force due to that of the conductors on either side.

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With drum winding the same is required; the winding, as a whole, must be in opposition, the two halves being put in parallel by the brushes. Certain precautions have therefore to be taken, for it is not *any* number of coils that will serve in this case, though many different combinations may be made. Consider the diagram, Fig. 73, in which the straight lines represent connections at the commutator end, while the curved lines indicate connections at the other or back end. It will be seen that the winding goes round the armature twice by being connected to every alternate conductor, eventually closing on itself. This is only possible by having both the front and back pitches of the coil, *i.e.* the number of coil legs spanned by the end connections, an odd number; thus in Fig. 73, conductor 1 is connected to conductor 6, thus spanning five conductor bars. Again, at the front, conductor 1 is connected

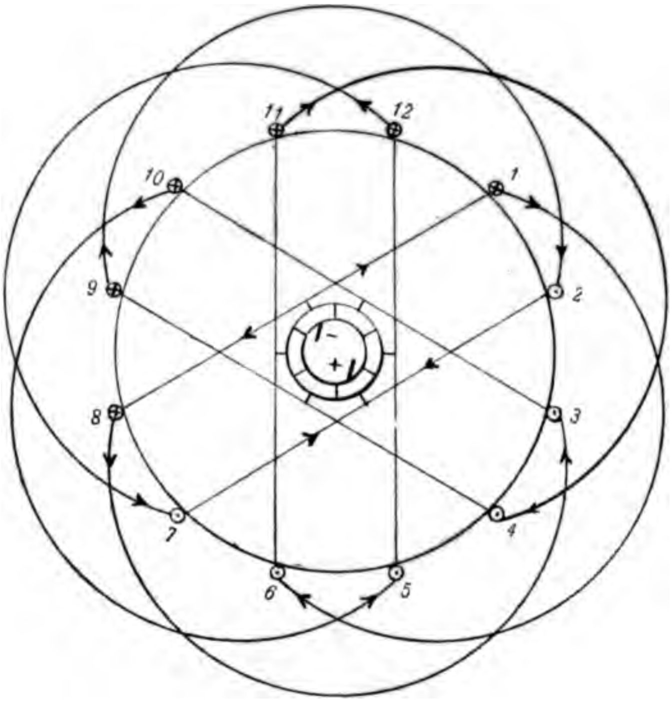

FIG. 73.

to conductor 8, thus spanning seven bars. By conductor bars is here meant the sides of the various coils that go into the slots. A coil may have any number of turns, but forms two bars only. With either front or back pitches an even number, the winding either will not close on itself, or it does so before including all the conductors.

The following is a general statement for the pitches of any drum winding:—

$$\text{back pitch} = \frac{\text{N} \pm x}{\text{No. of poles}} \pm 2 = \text{odd number}$$

$$\text{front pitch} = \frac{\text{N} \pm x}{\text{No. of poles}} = \text{odd number}$$

where N represents the total number of armature bars or coil legs, and x any whole number or nought. Thus in Fig. 73, N is equal to 12, and—

$$\text{back pitch} = \frac{12 - 2}{2} + 2 = 7$$

$$\text{front pitch} = \frac{12 - 2}{2} = 5$$

The pitch may be shortened till it spans but little more than quarter of the total armature bars; but we cannot go too far in this, for then the two conductors connected together are, at certain parts of a revolution, cutting through the same field, and therefore acting differentially. It should be taken as a rule that the pitches should span as near a diameter as possible. This will be seen by taking the front pitch in the above case as $\frac{12 - 6}{2} = 3$. We then get the winding shown in Fig. 74, where at times certain conductors are in opposition.

Let us now consider a case where we have more conductor bars, though with a large number the diagram becomes rather complex and not so easy to follow. Fig. 75 represents an armature with twenty-four such bars. Here the pitches are 9 and 11, or back pitch $= \frac{24 - 2}{2} - 2 = 9$, while front pitch $= \frac{24 - 2}{2} = 11$. We might, however, arrange the winding with a shorter pitch; thus in Fig. 76 the same number of bars are connected with back pitch $= \frac{24 - 6}{2} - 2 = 7$, and front pitch $= \frac{24 - 6}{2} = 9$.

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Beyond this point, any further shortening of the pitch leads to differential action.

When the coils are former wound, *i.e.* wound on special frames to the required shape, from which they can be easily removed, taped up, and dropped or pushed into the slots, it is usual to place one leg of a coil to the bottom and the other to the top of the slot. Fig. 77 represents the armature with twenty-four bars, as before, arranged two in each slot.

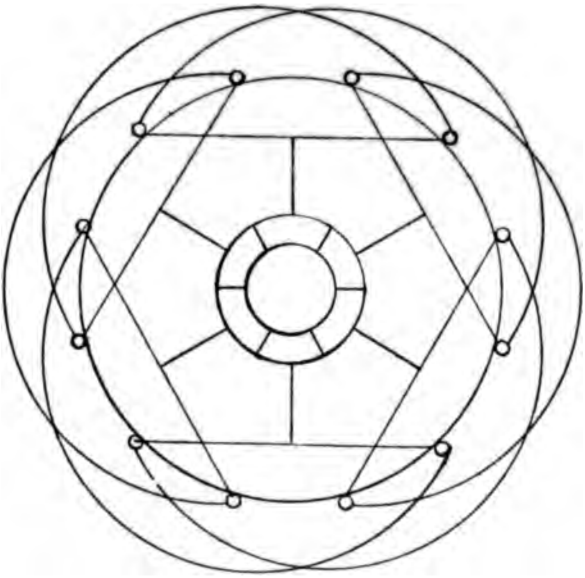

FIG. 74.

There are many different methods of winding the armature coils, the difference being in the arrangement of end connections. In some the winding is bent down at the ends of the armature, while in others it is kept straight. The former is known as evolute and the latter as barrel winding.

Perhaps the simplest method of forming the coils—applicable more to multipolar than to bipole machines, owing to the large pole pitch of the latter—is to wind them round two pins fixed a certain distance apart. The coils at most will have but a few turns each, and these are then taped together. Sometimes two or

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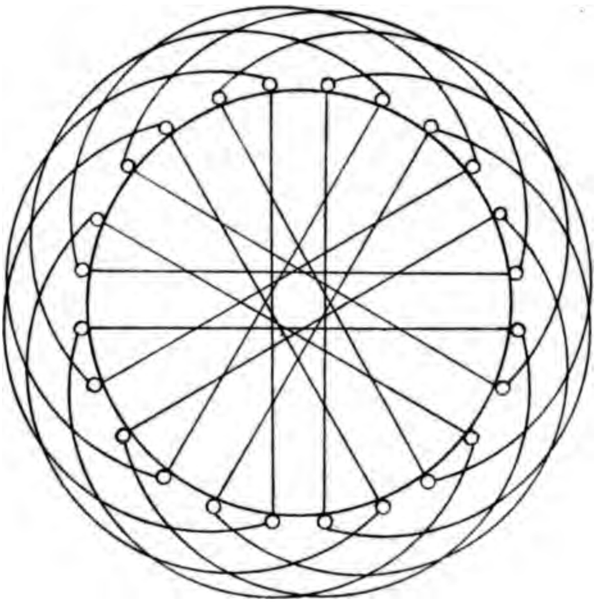

FIG. 75.

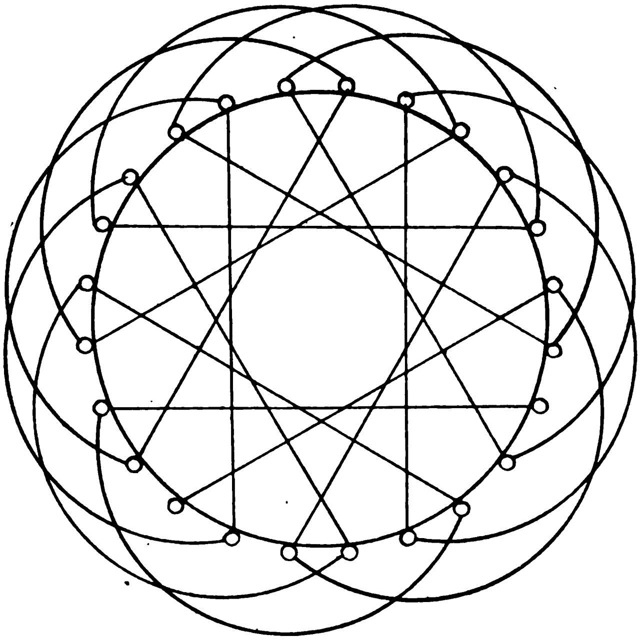

FIG. 76.

three such coils are bound together to go into one slot, especially where the turns per coil are but one or two. The coil is then taken off the pins and clamped at both ends, while other clamps, a little longer than the armature face, are fixed, one on either side, at the centre. These latter clamps are then pulled apart till the coil is wide enough to be sprung into the slots (see Fig. 78). The coils are now further insulated with tape, after which they are often soaked in some insulating varnish and baked dry, this process being repeated if the machine is for a fairly high voltage.

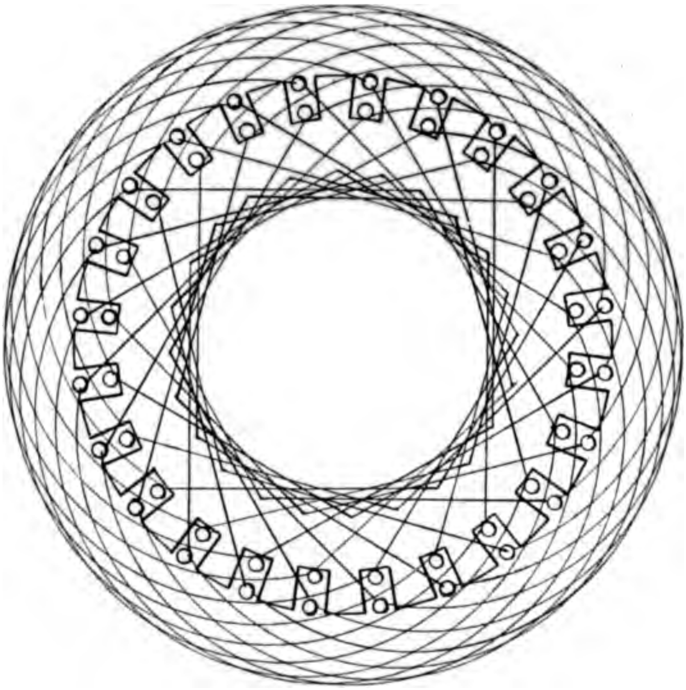

FIG. 77.

The ends *e*, *f*, of coils so formed may be left standing out straight, with the sides *ae*, *bf*, *ec*, and *fd* curved round, as shown in Fig. 78; we then have what is known as the barrel type of winding. The advantage of this is that both the core and the coils are free to receive the full benefit of air cooling; but, of

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course, projecting in this way, the over-all dimensions of the armature are considerably greater than where the ends are bent down, forming what is known as an "evolute" coil.

The projecting ends of the coils are not strong enough to support themselves against centrifugal action, and therefore have usually to be bound to a flange projecting from the end plates of the armature core.

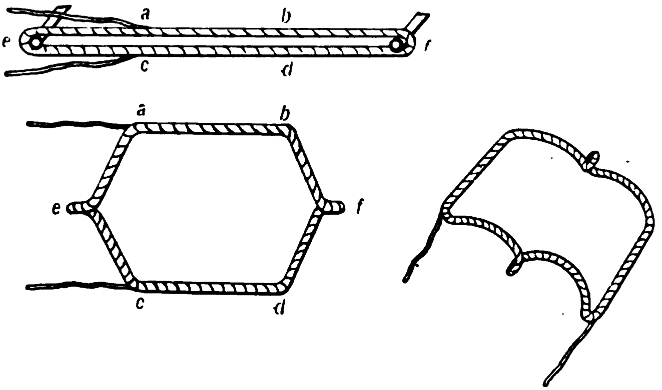

Fig. 78.

The slots are first insulated by a strip of presspahn, micanite, or other insulating material. One leg of each coil is then pushed down to the bottom of a slot, with the free ends of each facing the commutator, the other leg standing up above the core. After going right round in this manner, a second piece of insulating material is put on top of the coil legs in the slots, and the outside legs of each then pulled round and gently pushed into its proper slot, on top of the one already in. The ends are then soldered to their proper commutator sections. Fig. 79 shows a section of the slot with three turns per coil insulated in place.

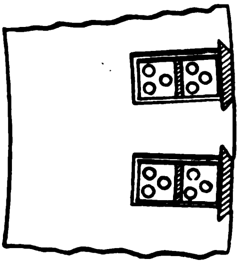

Fig. 79.

When we consider the amount of insulation on the wires, between the two sets in a slot and between the sets and the walls of the slot, it will be seen that the sectional area of the copper forms

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but a small portion of the total sectional area of the slot. Of course, the higher the voltage generated the greater must be the insulation allowed; but for any given output, the greater the voltage the smaller is the current required, and therefore the smaller will be the conductors. The same size slots will therefore serve for both, for with small voltage and large current we have more copper and less insulation, and *vice versâ*. The ratio of the sectional area of the copper in the slot to the sectional area of the slot is called the *space factor*. This varies from 0·3 to 0·5.

An evolute coil may be formed by winding the coil as before, but afterwards bending it at right angles at both ends, or the coil may be wound to shape in the first place, as shown in Fig. 80.

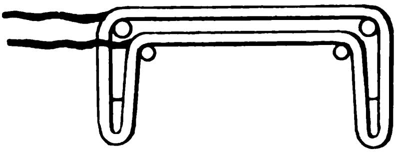

FIG. 80.

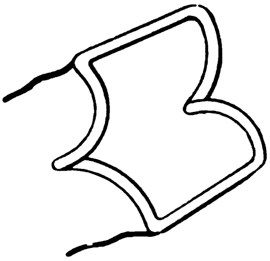

FIG. 81.

The two legs *ab*, *cd* being then clamped and pulled apart, we get the evolute coil shown in Fig. 81.

In large-sized armatures, delivering large currents, the conductors have to be massive; stout copper bars therefore take the place of the wire coils, and these cannot be bent in the same way. The usual practice in such cases is to build up the barrel or evolute coils by riveting and soldering to the ends of the bars separate copper connectors cut to the required shape. In some cases the copper bars are made up of a number of thin strips, placed side by side, *i.e.* laminated instead of solid, while in other cases stranded copper cable is rolled to a rectangular section. In each case the object is to avoid eddy currents, which may be induced in the body of such thick conductors, due to opposite sides cutting through fields of different strength at certain periods during a revolution, particularly at the horns of the pole pieces, where the field begins to fringe out. Stranded cable gets over the difficulty, for any one wire of the strand must be as much in the weaker as in the stronger part of the field at any time, and therefore all wires will have equal electromotive forces induced in them. To obtain the same result with the copper strip, they are given a half turn at or near their centre.

To form an evolute winding with large bars as described above, broad strips of copper, sawn down the centre, and pulled apart, are sometimes used as connectors (see Fig. 82). These have to be riveted as well as soldered to the ends of the bars, which are arranged projecting alternately long and short at both ends. These connectors have to be insulated, carefully and neatly, so as not to take up too much space. This is sometimes done by means of silk or other good insulating tape, and after being bound they are coated with shellac varnish and baked.

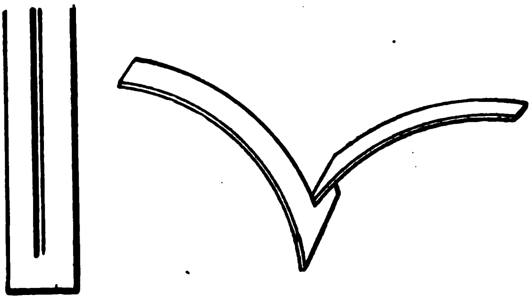

FIG. 82.

With the largest-sized bar windings the end connections are often built up by riveting and soldering together a number of parts, as shown in Fig. 83, for an evolute winding; the barrel winding being more commonly formed by bending the conductor bars at the ends till they meet one over the other, and then riveting clamping pieces to connect them together. The clamping pieces, *a*, *b*, in the evolute winding require some support. They may be supported by binding to a flange projecting from the armature end plates, though sometimes they are fixed by dovetailing, similar to commutator bars, in which case they have to be insulated with mica or other insulating material in a similar manner.

It has been pointed out that, except for the smallest sizes,

[redacted]

drum windings are much more commonly employed than ring windings; the diagrams of the former are, however, more complicated, and not so easy to trace out as the latter, and for this reason only, in subsequent explanations, where an armature winding diagram is required, a ring winding will be taken as illustration. The effects obtained by the two are in the main the same, and therefore the one will serve as well as the other for purposes of illustration, but without this preliminary explanation, the student may be led to suppose that ring windings are the more commonly employed of the two.

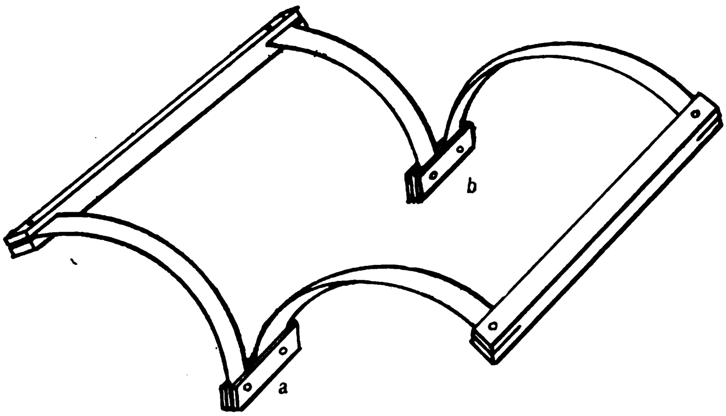

FIG. 83.

The purely mechanical parts of dynamos, such as the shaft, bearings, pedestals, bedplate, etc., are not very different from the same parts applied to other machinery, though we get, in some designs, strains which do not occur in other machines. With shafts we have to provide against the ordinary bending moment due to the weight of the complete armature and commutator, also for the twisting strains which arise from transmission through it of the energy supplied by the steam engine to the rotating conductors, and also to a possibility of unbalanced magnetic pull, which may be acting with or against the force of gravity. It will be remembered that the clearance between armature and field is very small in many cases, and therefore the shaft must be exceptionally stiff so that there shall be no deflection possible. The armature core, however, gives a very material stiffening at the centre, where it is most required, and therefore acts as a set-off against its weight.

Formulæ for size of shafts for any given power transmitted, running at any speed, are given in most engineering pocket-books. From Fowler's "Electrical Engineers' Year Book" we have—

$$\text{diameter of shaft} = 7\sqrt[3]{\frac{\text{HP}}{\text{revs. per minute}}}$$

which introduces a factor allowing for magnetic pull. This is a very liberal allowance, especially for large sizes, and gives an exceedingly stiff shaft.

In connection with high-speed machinery, there is a critical speed at which excessive vibration is set up. This is of great importance in turbine-driven dynamos, and to a less degree in other machines. It occurs at a point where the natural period of transverse vibration of the rotating part is equal to the frequency of the impulses given to it by centrifugal force acting on any slight want of balance, or slightly bent shaft. Professor Dunkerley gives the critical speed as—

$$s = 9{\cdot}55\sqrt{\frac{F \times g}{W}}$$

where F is the force in pounds necessary to bend the shaft 1 foot at the point of attachment to the rotor, W the weight of the rotor and a portion of the shaft in pounds, and g the acceleration due to gravity (= 32). Behrend gives for the same—

$$s = \sqrt{\frac{KEI}{Wl^3}}$$

where K is a constant of value about 75, E the modulus of elasticity, I the moment of inertia, W the weight in pounds, and l the length between the bearings.

Some makers allow a little end play in the shaft, which tends to keep the commutator from wearing into grooves or ruts. Where this is done the amount allowed should be small—not more than $\frac{1}{16}$ inch or thereabout.

Dynamos, as a rule, run at a fairly high speed, and are often required to do so for long periods without stopping. Special attention has therefore to be paid to the bearings, which should be rather longer than for other machinery, and of the self-lubricating type. It is also essential that the oil be kept from creeping along the shaft and on to the commutator. Seeing that little or no wear of the bearings or tightening up of the brasses is allowable, they are often made of the solid self-centring type; split bearings are used in most of the larger sizes, but this is more to facilitate the insertion or removal of the armature than to allow for tightening up.

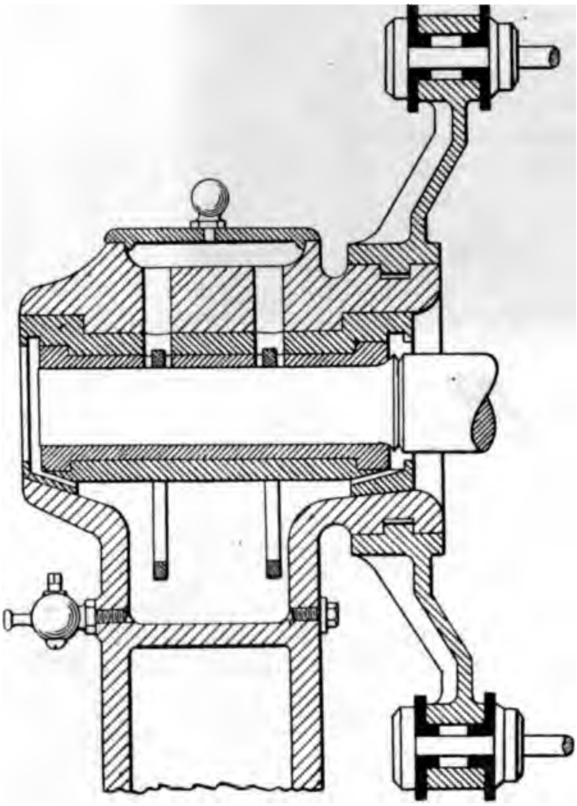

FIG. 84.

[redacted]

The ends of the bearings are usually provided with hoods to catch the waste oil thrown off by a ring projection on the shaft, the oil then draining into a tank or well cast in the bearing. The lubrication is often effected by cutting away the brasses at the upper surface in one or two places, and slipping over them brass rings, which then come in contact with the shaft at these parts. The lower part of each ring dips into the oil well, and as the shaft rotates it carries the rings round also, and in this way oil is automatically carried from the well to the shaft (see Fig. 84). The brasses are best tapered inwards slightly where they are cut away for the oil rings, for when slanting outwards, the sharp edges

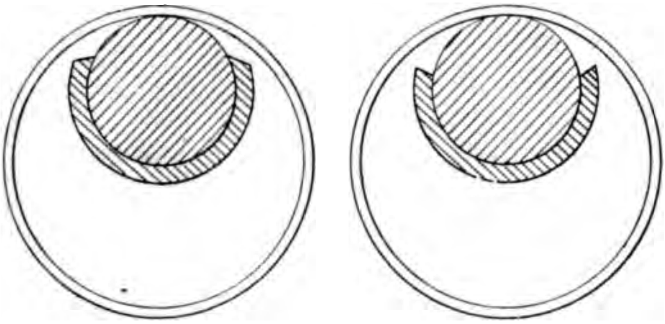

FIG. 85.

so formed tends to scrape the oil off, instead of feeding it in. This is shown in Fig. 85. The oil throwers on the shaft are usually formed by turning a recess in the part to be covered by the hood, the oil by centrifugal action is then carried to the edge, and there thrown off, the groove thus effectually insulating from oil all parts beyond it.

Owing principally to the persevering work of the Hon. C. A. Parsons, the steam turbine has been developed to such a high degree of perfection as to equal, if not surpass, the performance of the best reciprocating engines, and along with this development has followed that of a special class of continuous-current dynamo suitable for turbine driving. Mr. Parsons should be credited also with overcoming the difficulties attending the successful design of these high-speed machines, for most of the special difficulties attending the high speed—often as high as

[redacted]

eighteen thousand revolutions per minute in some of the earliest machines—have had to be met and overcome, before the applications of the turbine in direct-current stations became possible.

One of the chief difficulties is in the commutator, for, owing to the very high centrifugal force, the tendency for the bars to bulge outwards is very great. This difficulty has been overcome by shrinking steel rings over the commutator with mica between, at three or four points. The bars are first built up in the ordinary way, as described on p. 85, after which rings of mica are tied on at equal distances apart, depending on the length of the commutator. The rings are then shrunk on, and the commutator and rings machined all over. The inside ends are turned conical, and the complete commutator is then forced on to a mica insulated cone fixed on the shaft, and a second similar cone forced in the other end by locknuts. The two end rings often have grooves cut in them, which facilitate the easy adjustment of small balance weights (see Fig. 86).

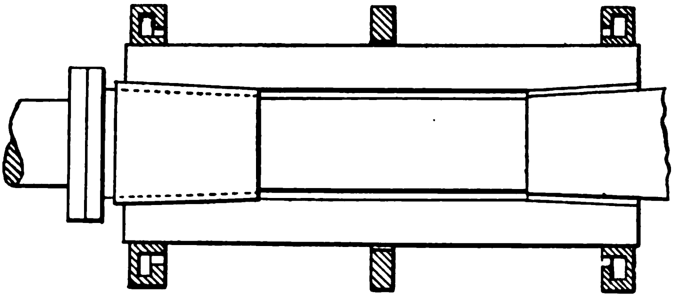

FIG. 86

Carbon brushes cannot be employed with turbine dynamos, for, owing to the armature floating when running, the brushes vibrate a great deal. Even stiff metal brushes are unsuitable, the best results being obtained with brushes made of bundles of soft brass wire. To get the necessary brush contract area, without an undue length of commutator, the commutator face in many of the early machines was turned into a series of grooves. The soft wire brushes fit themselves into these, and wear the whole equally. At the high speeds employed, the wear is more rapid than with slower-running machines, but owing to the method of support, the

[redacted]

bars can be worn down to less than half their original depth before the commutator need be renewed.

In the earlier types it was necessary to alter the brush lead with changing load, and an ingenious device was invented for doing so automatically. This consisted of a piston working in a small cylinder with a spring control, the piston-rod being attached to the brush-rocker. The steam pressure inside the turbine at one point was found to be proportional to the load, and so, by connecting this part with the cylinder, a movement of the brushes was obtained proportional to the load. In the latest machines, however, commutating poles or compensating windings—the action of which will be explained in the next chapter—are employed so that the brushes remain fixed for all loads, and the brush-shifting device is dispensed with.

In many machines intended for turbine driving, especially in small sizes, the armature conductors are wound on smooth cores, bound with a double layer of piano wire all over; but most of the larger sizes are now made with semi-enclosed slots and wedges to keep the conductors in place, special clamps being provided for the end connections, as shown in Fig. 87.

The radiating surface in turbine-driven dynamos is relatively small, owing to the small over-all dimensions, but the losses for any given output are not much smaller. This has led to a considerable increase in the ventilating spaces, and in some cases to forced ventilation. It is not uncommon in such machines to find one ventilating duct to every 2 inches of armature core length.

The number of poles should be as large as possible, so that the armature ampere turns per pole shall not be excessive, and yet small enough to keep the frequency of commutation and the periodicity in the armature core to reasonable values. As a rule, the latter should not exceed eighty cycles per second, and should be considerably less if the magnetic density be at all high.

From the above considerations it will be seen that the difficulty of designing direct-current machines for such high speed increases considerably with the output, and where large outputs are required, two machines are usually coupled to the same turbine shaft.

The maximum peripheral speed of the armature is limited by the centrifugal force acting on the winding and insulation, and this rarely exceeds 15,000 feet per minute, 12,000 being a safer and better figure to employ where possible. In most cases, owing to the small diameter, a spider is unnecessary, and a much better mechanical construction is obtained by employing discs pierced with ventilating tunnels directly keyed to the shaft.

The armature slots are very frequently of the open-notched-ended type, illustrated in Fig. 79, which allows of former wound coils; but some makers prefer either closed slots or partially closed slots, as represented in Fig. 50. These assist somewhat in procuring sparkless commutation, and give a better support to the armature winding, though the labour of winding is considerably enhanced.

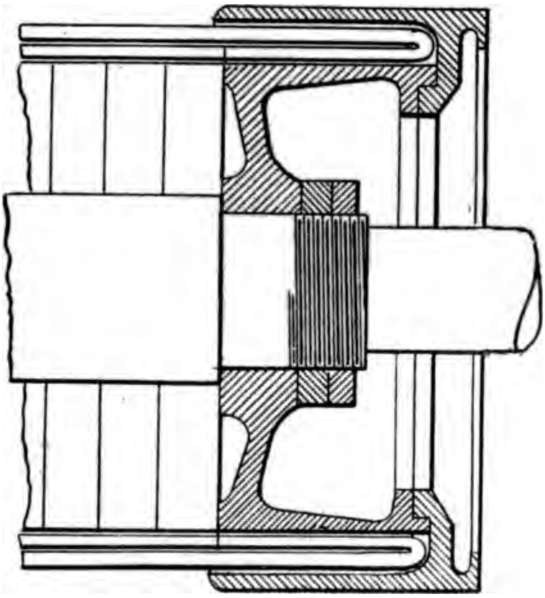

FIG. 87.

CHAPTER VIII

THEORY OF BIPOLAR MACHINES

Consider the action of a machine such as we have described in the last chapter. The current in every conductor reverses twice at each revolution, at a time when the conductor or coil passes under a brush. The time occupied in the reversal is therefore exceedingly short; thus, suppose the armature be 6 feet in circumference, wound with, say, 60 separate coils, and to be running at six hundred revolutions per minute, or ten revolutions per second, then each coil moves over 60 feet each second. A coil in passing a brush will do so in little more than $\frac{1}{60}$ of the time taken in making one revolution, therefore in $\frac{1}{60}$ of $\frac{1}{10}$ second. In this case the current in each coil has to be stopped and a reverse current started in it of the same value in the $\frac{1}{600}$ part of a second.

Now, we have seen that each coil has more or less inductance, which tends to prevent the dying away of the one, or the starting up of the reverse current; the inductance depending on the magnetizability of the circuit and the square of the turns in the coil. It will be noticed that while a coil is passing under a brush, it is, for the time being, short-circuited by the brush, and forms a local circuit of very small resistance. Up to the instant at which the short-circuiting begins the coil is carrying its normal current, equal to that carried by all the conductors on the same side, and equal to half the current delivered to the outside circuit. When the short circuit is removed by that particular coil breaking away from the brush, it has to carry the current generated by the conductors on the opposite side, which is in the reverse direction to that carried by it a moment before, for, being put in series with them, no other path is open for the current to take, unless it sparks across the commutator face to the brush as the coil recedes. Now, the latter is very apt to occur, for the inductance of each coil resists the sudden change required to reduce the current from

[redacted]

its full value to zero, and build up the reverse current to its full value in so short a time, and unless this is accomplished during the time the coil is short-circuited by the brush, sparking must take place.

To generate in itself a reverse current the coil must, while short-circuited, generate a reverse electromotive force to that which it had previous to being short-circuited; that is, it must cut through the field in the reverse direction. At the extreme top and bottom of its travel, in the plane at right angles to the line joining the centre of the pole pieces, each coil will be generating no electromotive force whatever, for here the coil is practically sliding through the field rather than *cutting* through it, and therefore if the machine be delivering no current, *i.e.* on open circuit, this will be the correct position for the short-circuiting to take place, for then no current can flow round the short circuit. But if the machine be delivering a current, it will be necessary to generate a small electromotive force in the reverse direction, so as to build up a short-circuit current equal to that carried by it after the short circuit is removed. To accomplish this, it is necessary to swing the brushes forward a little so that the short-circuiting shall take place while the coil is cutting through the field in the reverse direction. A very small electromotive force would be sufficient to generate a large current in a coil of such low resistance; but we must remember that a relatively high back electromotive force will be induced in the coil equal to $2\pi n\text{LI}$, owing to the flux due to the current in the coil cutting its own conductors as the current dies away and the new current grows. This in known as the reactance voltage of the coil (see p. 53).

The frequency n in the above formula will be equal to the peripheral speed of the commutator in inches or centimetres per second divided by twice the thickness of the curved surface of the brush in inches or centimetres. The reversal begins the moment a segment touches the heel of the brush, and finishes as it leaves the tip. The time of reversal is therefore the time taken by the segment in passing across the face of the brush; but this reversal is only equivalent to half a cycle, and therefore the frequency in cycles per second, as represented by n in the above formula, will be obtained by dividing the peripheral speed by twice this time.

The inductance L can only be calculated approximately. It represents the interlinkings of lines and turns per ampere produced by the flux and the turns in the short-circuited section, divided by 10^8 (see p. 53). Values obtained by any rule, though very useful by way of comparison, can only be taken as relative.

Mr. Hobart gives values for the lines of force due to that part of the winding embedded in the slots as 4 per ampere turn per centimetre length of the winding, and 0·8 line per ampere turn per centimetre for the free part forming end connections. The total interlinkings of lines and turns in the short-circuited coil per ampere will therefore be equal to total length of embedded portion $\times$ 4 + total length of free portion $\times$ 0·8.

$$\text{The inductance} = L = \frac{\text{total interlinkings per ampere}}{10^8}$$

The reactance voltage is therefore—

$$= \frac{2\pi P \times \text{total interlinkings per ampere} \times \text{current}}{2t \times 10^8}$$

where P = peripheral speed of the commutator in inches per second, and t the thickness of the brush in inches.

Suppose the coil short-circuited by the brush to have four turns, drum wound, carrying a maximum current of 50 amps.; length of embedded portion per turn = 80 cms.; length of free portion = 160 cms. Further suppose the peripheral speed of the commutator to be 2000 feet per minute = 340 inches per second, and the width of the curved surface of each brush 0·5 inch, then—

$$L = \frac{80 \times 4 \times 4 + 160 \times 4 \times 0{\cdot}8}{10^8} = 0{\cdot}00001792$$

The reactance voltage will therefore be—

$$v\ 6{\cdot}28 \times 340 \times 0{\cdot}0000179 \times 50 = 2 \text{ volts}$$

The farther we move the brushes round, the stronger will be the field in which the short-circuiting takes place, and consequently the higher will be the induced electromotive force in the short-circuited coil. But we only require the higher electromotive force to counteract the higher reactance voltage as the load increases, and therefore, theoretically, there is a best or proper position for the brushes on the commutator for each change in the load.

Of course, the volts to be generated in the coil during commutation must not only be sufficient to counteract the reactance voltage, but must also provide the CR voltage to generate the reverse current. The latter, however, is usually small compared with the former, so that the vectoral sum of the two, which is the required value, is practically equal to the reactance voltage alone. It will therefore be seen that to facilitate sparkless commutation the reactance voltage of each coil should be made as small as possible.

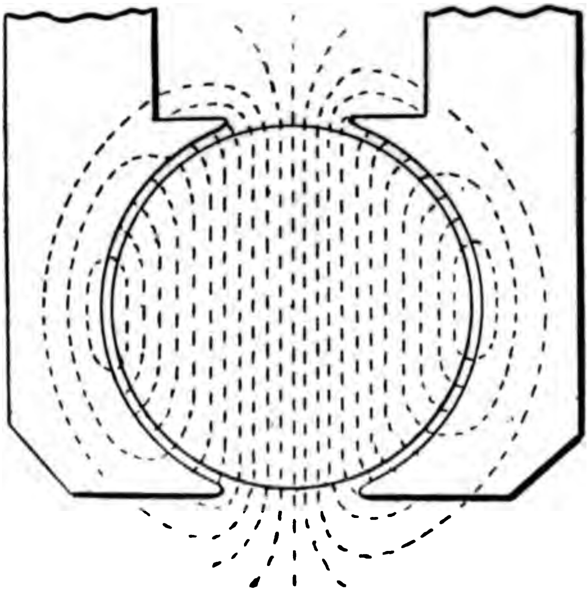

FIG. 88.

Other things being equal, the reactance voltage is proportional to the square of the turns, therefore it is advisable, especially in large-sized machines, to reduce the turns per commutator bar to the minimum. This necessitates a larger diameter and more expensive commutator, for there is a minimum thickness for the commutator bars depending on the current to be collected, and therefore more bars can only be obtained by increasing the diameter. The reactance voltage also depends on the magnetizability of the short-circuited coil. If the coil be wound in deep narrow slots, it will have much more inductance than the same number of turns wound in wider and more shallow slots.

When the armature conductors are carrying current, the core is magnetized by the ampere turns so produced, in a direction practically at right angles to the main magnetization of the core; this cross magnetization being proportional to the load (see Fig. 88). The two magnetomotive forces will therefore give a resultant flux across the armature core, the distortion or inclination of which will vary with the load (see Fig. 89). The direction of the armature current and motion of the conductors in the main field producing the current may be obtained by the hand-rule mentioned on p. 38. From this it will be seen that the direction of the cross field is such as to give a resultant which weakens the field at the leading pole tips and strengthens it at the receding tips. This is in exact opposition to what we desire, though it is unavoidable, for if we reverse the main field, or the direction of rotation, we at the same time reverse the direction of the current in the armature conductors, and so obtain the same result. We have

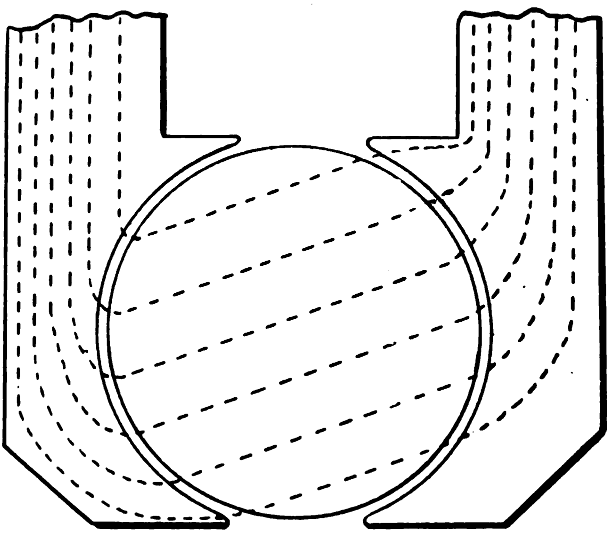

Fig. 89.

seen that it is necessary to advance the brushes to develop the required voltage in the short-circuited coil or coils, but owing to this weakening of the field at the pole tips the necessary amount of brush movement is considerably increased. This effect is known as *armature reaction.*

Sparkless commutation would be greatly facilitated, with less movement of the brushes, if the armature reaction were small, but this can only be obtained by keeping the number of conductors on the armature as small as possible, and making up the required electromotive force by using stronger magnetic fields. This will also react in another way. The main field being stronger, any given armature magnetomotive force will have less distorting effect on it, so that for sparkless commutation the armature strength, measured in the number of ampere turns produced at full load, should be kept as small as possible, while the main field should be strong.

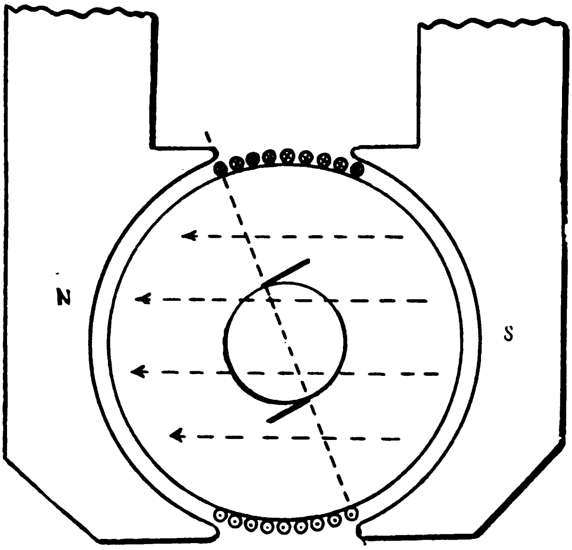

FIG. 90.

The forward movement of the brushes brings a demagnetizing action into play, which will also be less the smaller we make the armature strength. While the brushes were in the mid-pole

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position, the combined armature current produced only a cross magnetization effect, but with the brushes advanced beyond this point, a certain number of conductors at both top and bottom are carrying current in a direction tending to demagnetize the armature (see Fig. 90). The whole winding may be considered as providing two armature magnetomotive forces, the one due to the conductors included in twice the angular displacement of the bushes, giving rise to so many back ampere turns, the other due to the remainder of the winding producing a cross magnetomotive force. The back magnetomotive force of the armature is directly opposed to the main field ampere turns, and has to be counteracted by additional excitation of the field magnets as the load increases.

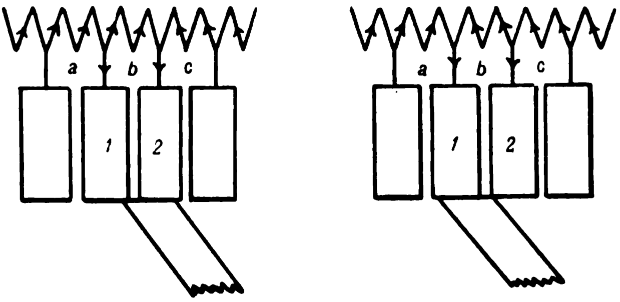

FIG. 91.

The resistance of the brush contact in the circuit of the coil undergoing commutation has a very material effect where carbon brushes are employed, for the surface or contact resistance with them is much greater than with copper brushes. This resistance is small when considered in connection with the machine as a whole, but is large compared with the resistance of a single coil short-circuited by them.

Brushes made of a mixture of carbon and metal dust have also been employed. These have a lower specific resistance than pure carbon brushes, but their commutating properties are inferior, and an oxide of the metal employed is apt to form round the commutator face.

Consider Fig. 91. At the moment when the tip of the brush comes into contact with the advancing commutator bar (1) a relatively high resistance is put into the short circuit, and current enters the brush through commutator segments (1) and (2) from the short-circuited coil (*b*) and from the coils in advance (*a*). A considerably larger current therefore enters the brush by segment (2) than by (1), owing to the higher resistance of the latter circuit. This causes a difference of potential between segments (1) and (2) and the brush, tending to urge a current round the short-circuited coil in the reverse direction. Thus the short-circuit current in the coil produces an effect tending to stop it, and this will continue until the current density in the two segments is alike, the current in the short-circuited coil being in part reduced to zero in this way. As the coil advances, the current entering the brush by coil (*c*) now divides between the commutator segment (2) and the coil (*b*), for the two are in parallel, the current therefore dividing in inverse proportion to their resistances. Again, the contact resistance assists in the growth of the reverse current, for, being relatively high, the current through coil (*b*) rises quicker, and as segment (2) passes out of contact with the brush, the resistance of that circuit increases more and more, till finally the whole of the current from (*c*) passes through (*b*) to the brush. With copper brushes the contact resistance is very much smaller, and even up to the point where segment (2) is on the verge of breaking away from contact with the brush is so small as to practically give rise to none of the above effects.

Some makers have adopted the plan of making the commutator lugs of iron or German silver, so as to have more resistance. In this case the current only passes in parallel through the lugs connected to the bars under the brushes, and therefore they do not seriously affect the resistance of the machine as a whole, but the same resistances are in series in the circuit of the short-circuited coil, which makes its time-constant shorter, and so facilitates the change in the direction of the current.

Graded carbons—*i.e.* carbons in which the leading tip is softer and of lower resistance than the trailing tip—have recently been introduced, and are said to give very good results.

A great many devices have been tried to minimize the effects of armature reaction with more or less success. The magnitude of the armature cross field depends, as in every case, on the magnetomotive force operating and on the magnetic reluctance of its circuit. With any given number of armature conductors and full-load current, the magnetomotive force is fixed, but the reluctance of the armature cross circuit may be modified in many ways. The cross field might also be neutralized by providing an additional field in opposition to it, varying to the same extent.

The reluctance of the armature circuit must be increased without appreciably affecting that of the main field circuit, the greatest factors in which are the length of the air gaps and the teeth. Both air gaps and teeth come into the armature cross circuit also, more particularly at the pole tips, and consequently, by widening out the air gaps as they approach the tips, we considerably increase the reluctance in this circuit, without very materially affecting the main circuit (Fig. 92). A long narrow slot, cast in the field pole pieces in a direction along the length of the lines, as shown in Fig. 93, will have but a very small effect on the main field, while it puts this additional air gap in the

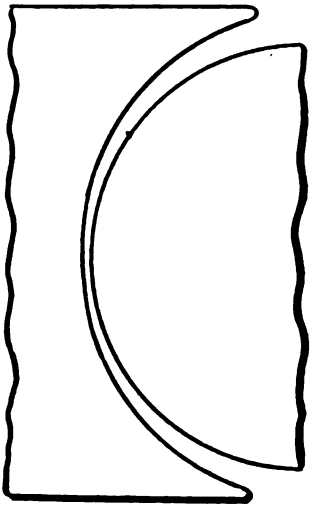

FIG. 92.

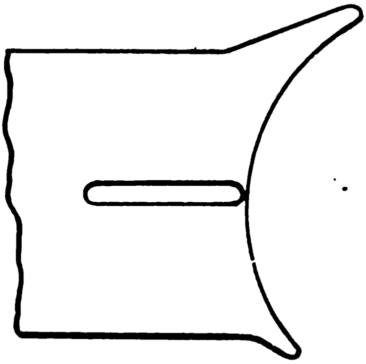

FIG. 93.

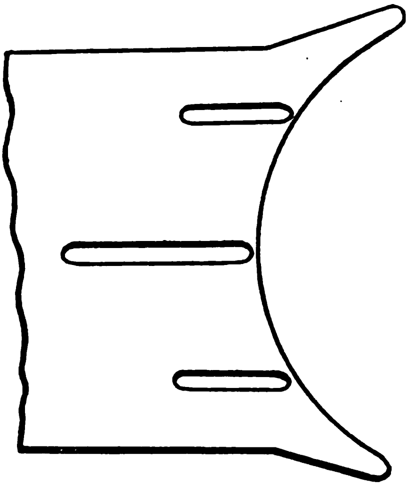

FIG. 94.

armature cross field circuit. This might be increased to two, or even three slots without much disadvantage, as shown in Fig. 94.

If the pole tips are run out rather thin, they become highly saturated by the main field; and at the high density so produced the reluctance there will be much lower than in the main body of the core. This, again, increases the reluctance of the armature cross field, and is a rather common practice. Another method is to make the pole tips of cast iron (Fig. 95); and in other cases separate pole shoes of cast iron are shaped and bolted on (Fig. 96). Cast iron has a much lower permeability than wrought iron, and will therefore be highly saturated by the main field; and coming into the armature cross circuit lengthwise, adds very considerably to its reluctance, though forming but a very small proportion of the total length of the main field circuit.

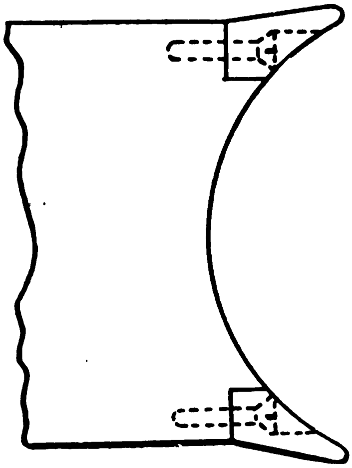

FIG. 95.

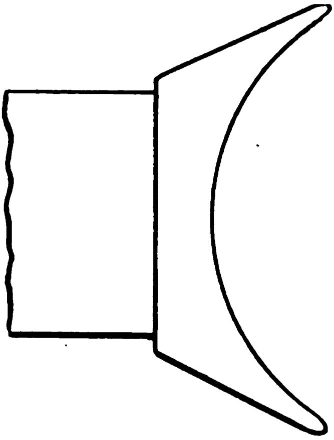

FIG. 96.

The addition of extra small poles in the interpolar space, to neutralize the armature cross field, has recently been revived, and is now being applied to many of the larger-sized machines. Originally, a winding, in series with the armature, carrying a current varying with the load, and therefore with the armature cross field also, was wound in holes in the pole tips, or in a slot cut in their face as shown in Fig. 97. This coil was connected up in such a manner that the direction of the field produced

[redacted]

by it was opposed to the armature cross field; but the required turns, to be equal to the cross-ampere turns of the armature, with such an open coil and with a partial air core, caused an abnormal drop in pressure at full load. The latest practice is to wind the

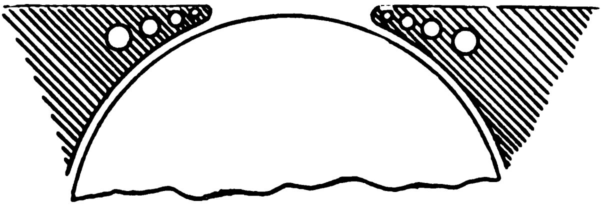

FIG. 97.

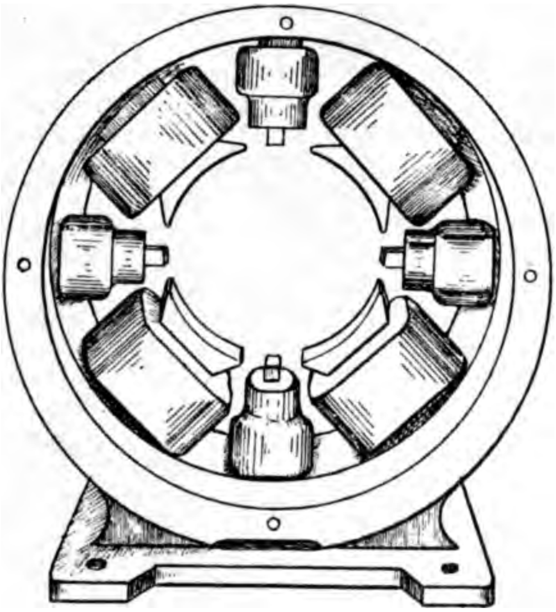

FIG. 98.

coil on a narrow iron or steel core, supported by a yoke in a similar manner to the main field-cores. The reluctance of this circuit is then very much diminished, and the required flux obtained with a much smaller series winding.

[redacted]

The space between the main poles is usually rather limited, so that the introduction of these commutating poles can often only be effected by a considerable cramping of the winding, which is not particularly easy with heavy series turns. In addition, they add to the heating of the machine, by interfering somewhat with the ventilation. It often happens that quite a small change in some detail alters considerably the heating of a machine by restricting or diverting the flow of air; and this must be kept in mind when introducing commutating poles. So much experimental work has been done and experience gained in the design of direct-current dynamos, and the requirements for sparkless commutation are so well known, that it would seem unnecessary to provide them, except, perhaps, in cases where the inherent sparking tendencies are particularly great, such as with the high speeds used in turbine driving, or extra high voltage machines.

Where commutating poles are employed, a number of ampere turns is required equal to the armature ampere turns, plus that required to get the flux through the auxiliary magnetic circuit, which includes the air gap and the teeth directly under the auxiliary pole face. This pole face should be slightly wider than the width of the slots which are carrying conductors short-circuited by the brushes during commutation. The number of armature slots, also, should be sufficiently numerous to prevent large changes in the flux of the reversing poles as they sweep past.

Where the interpolar space is somewhat restricted, it is best to arrange the auxiliary poles outside, and lead the flux to the armature core by inwardly projecting pole pieces.

It will be noticed that the armature cross field, producing magnetic distortion, passes twice across the air gap, and therefore, with a long air gap, the armature reaction will be less, owing to the smaller magnetizability of its circuit. A very large proportion of the total excitation ampere turns, however, are required for this part of the circuit, and on this account the air gaps cannot be made more than a few millimetres in length, though it is best to use as long air gaps as possible without too great a loss in the power required for excitation. The larger the machine, the greater is the armature reaction, and the loss in excitation forms a smaller proportion of the total losses; and the air gaps may, therefore, be longer the larger the machine. There is, however, no fixed relation between size of machine and length of air gap, though in a very fair number of machines of varying size the length of air gap falls approximately on a curve given in Fig. 99. It should be mentioned, however, that several machines, excellent in every respect, depart considerably from this curve.

The field magnets, wound with many turns of fine wire, may be excited from an independent source, such as a battery of accumulators or another dynamo; and by means of a rheostat in the exciting circuit the terminal potential difference may be maintained constant from no load to full load by hand regulation. A diagram illustrating this is shown in Fig. 100. By this arrangement, with close attention, a very constant terminal potential difference may be maintained, and, if required, the excitation can be adjusted to maintain a constant potential difference at a distance from the machine, in which case the *terminal* potential difference must rise with the load. The variations in terminal potential difference, with changes in load, are represented for the two cases in Fig. 101, where the full line indicates a constant terminal potential difference for all loads, and the broken line a steady rise at the terminals, to maintain constant difference of potential at some distant point. It will be understood that this is only obtained by close attention to the field rheostat. If the machine be adjusted in potential difference for no load, and then left to itself, armature reaction and C.R. drop will give a falling characteristic, as represented in Fig. 102.

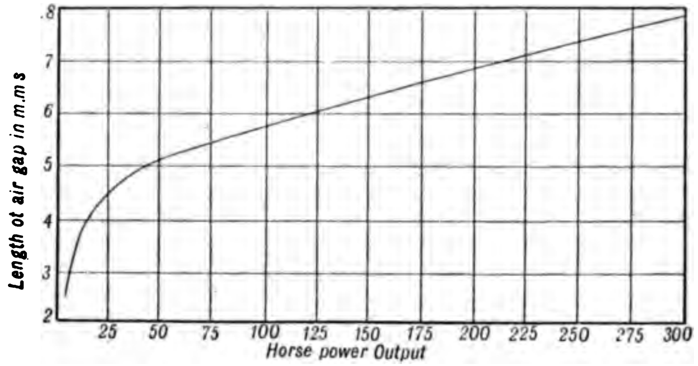

Fig. 99.

This method of exciting is used very extensively in machines

[redacted]

of large size, for an attendant is necessary in any case; and it is found possible to keep a much closer pressure regulation in this way than by any automatic arrangement. In special cases, such as dynamos used for power purposes, the fluctuations in the load are so great and so rapid that hand regulation is out of the question, in which case the machines have to automatically adjust the excitation with changes in load.

The dynamo may be made to excite itself however, independently of any auxiliary battery or plant, in one of two ways. Suppose the ends of the field winding, including the field rheostat, to be connected to the terminals of the machine, as shown in Fig. 103. We have seen that when working normally a potential difference is maintained on the terminals, and, there being a closed circuit round the field magnets, a current will flow which can be adjusted by the field rheostat to produce any required excitation, in exactly the same way as when connected to the battery. When the machine is at rest there will be no electromotive force at the terminals, and therefore no current can flow round the field circuit,

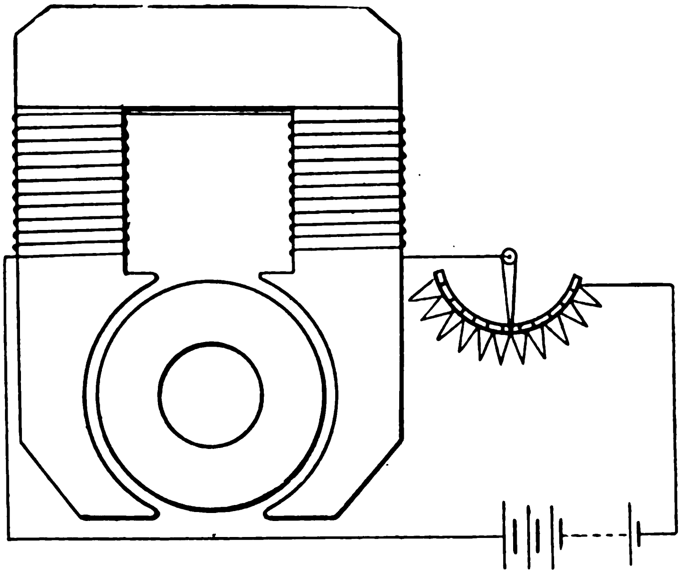

FIG. 100.

and consequently no excitation will be produced. But it will be remembered that on cutting down the exciting current to zero on

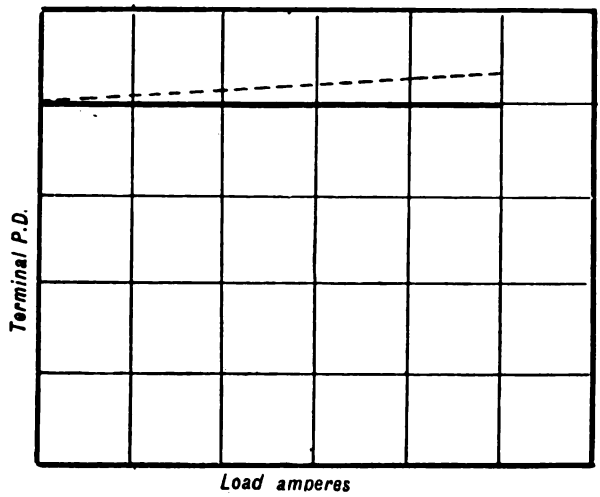

FIG. 101.

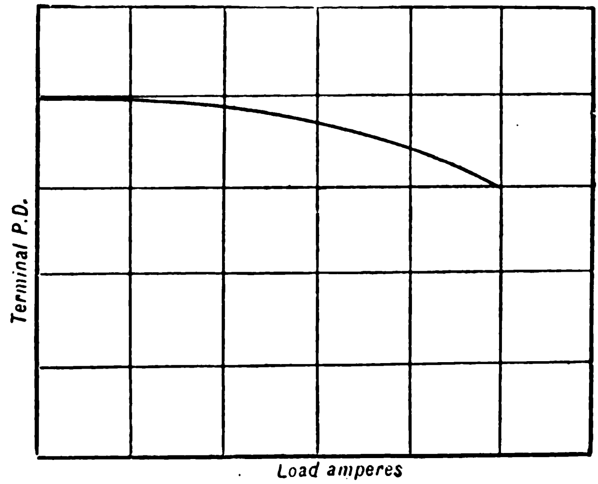

FIG. 102.

a large electro magnet, the whole of the flux does not disappear owing to the retentivity of the iron. In fact, in some cases nearly

[redacted]

half the full load flux remains (see p. 59). When the machine is started, therefore, it immediately begins to develop an electromotive force—of course, considerably smaller than the normal—and this gives rise to a small current round the field winding. This in turn excites the field further, and gives rise to a larger flux. In this way the machine rapidly builds up the electromotive force, so that a few seconds after starting we have the normal no-load potential difference at the terminals.

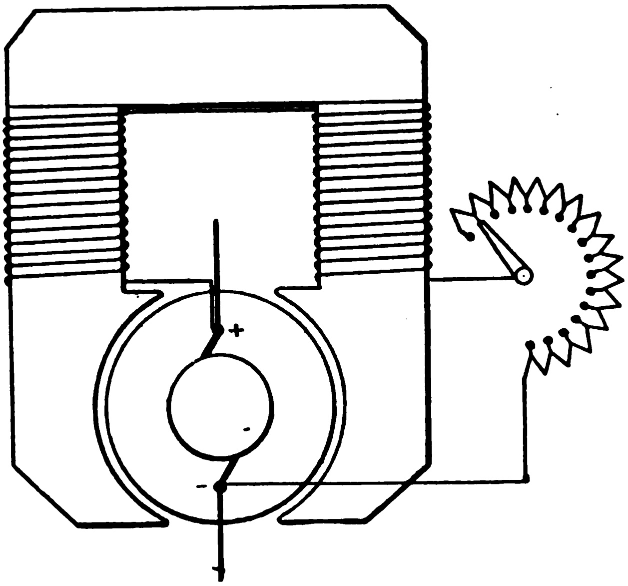

FIG. 103.

Such a machine, known as a shunt-excited machine, will be fairly constant in terminal potential difference over a large range; but it will not be so stable as the separately excited machine, and will require more adjustment for changing load. It will be noticed that armature reaction, producing back magnetization, etc., and also CR drop, had no effect on the exciting current when separately excited, for the potential difference in the exciting circuit was maintained constant by the battery. In this case, however, an increase in load will produce a drop in the terminal potential difference, and therefore in the exciting current, so that a greater variation will take place before there is a balance. If the field magnets are magnetized well over the bend in the magnetization curve, a slight change in exciting current will not produce much change in the flux; but as soon as the flux falls on or below the bend, the machine becomes unstable, and is of no service beyond this point. If we continue to increase the load current, we still further diminish the excitation, and eventually the electromotive force practically falls to zero, for now the outside circuit being so small in resistance, forms a dead short circuit on the field magnet winding, and consequently the current in it dwindles away to practically zero.

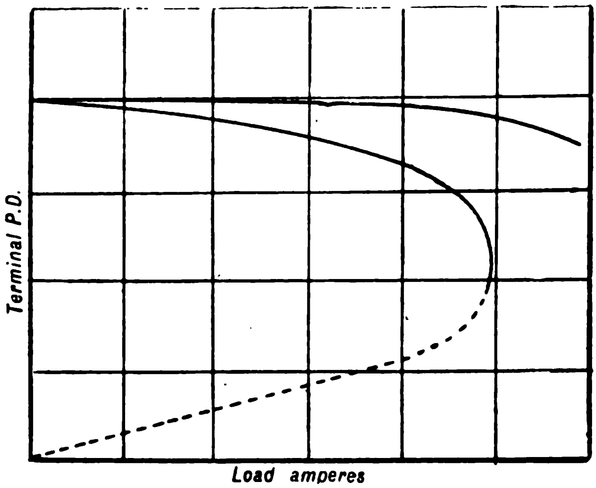

FIG. 104.

The characteristics of such a machine are shown in Fig. 104, in which, it will be noticed, the electromotive force remains fairly constant over the normal working range, owing to close adjustment of the field rheostat. With the same machine, left to itself, after adjusting the potential difference at no load, we should obtain a characteristic more like the lower curve, the dotted line showing the rapid fall in potential difference as the field winding is more and more short-circuited by the external circuit.

Consider the machine when dead short-circuited. It can develop no electromotive force, except the small initial value due

[redacted]

to the residual magnetism of the field magnets. In this condition the machine will absorb very little power above that required to run it at full speed against the friction of air and bearings. If this dead short-circuit be now removed by putting a very small resistance in the outside circuit, a small current will flow in the field winding, and the electromotive force developed will increase slightly. This growth in the electromotive force, with increase in resistance in the main circuit, will evidently continue right up to the maximum no-load electromotive force of the machine. At a certain point the machine will be delivering a maximum current, which, with further increase in the external resistance, will begin to decline, and by increasing the resistance from this point to infinity, the electromotive force rises to its maximum, while the current in the external circuit drops to zero. This characteristic is shown in Fig. 105. It will be noticed that the electromotive force rises in a similar manner to the rise in the magnetization of iron, with increasing excitation, but with a more rounded bend at the top. The electromotive force rises, only because the excitation rises, and therefore the two curves should be alike. The bend or knee of the curve is not so sharp as in the magnetization of iron curve, owing to the various parts of the

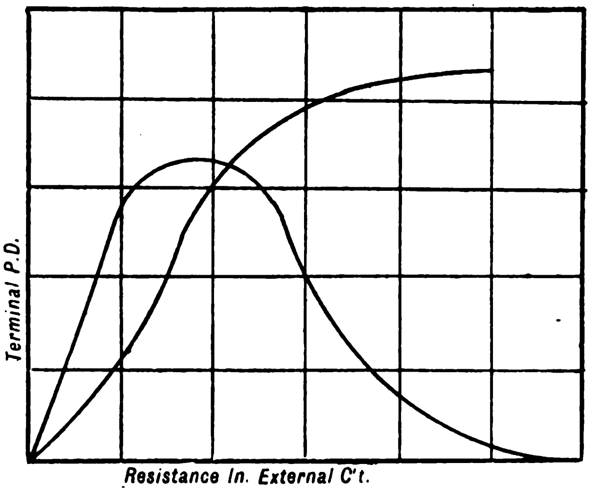

FIG. 105.

[redacted]

circuit becoming saturated at different times, and to the constant permeability of the air gaps in the circuit.

The machine may be excited in another manner, shown in Fig. 106, known as series excitation. In this case the field magnets are wound with relatively few turns of cable, large enough to carry the whole of the current to be delivered by the machine

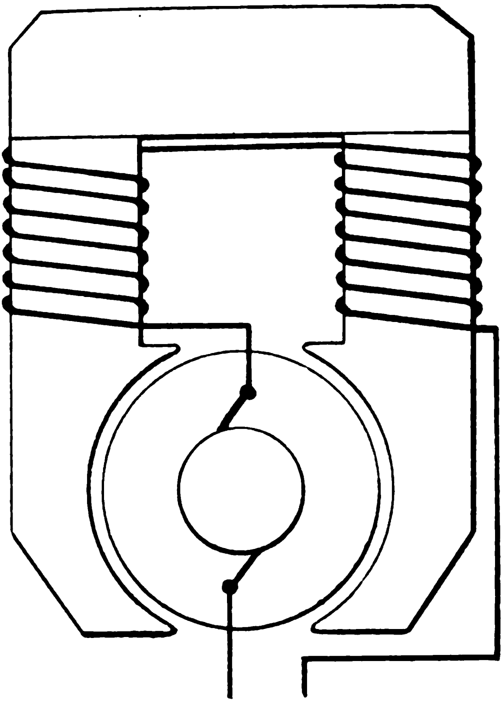

Fig. 106.

without an excessive drop in pressure, or absorption of power When the external circuit is open, the field-magnet circuit is also open, and the only electromotive force developed by the machine when running at normal speed will be that due to residual magnetism. If the circuit be now closed by a high resistance, such as a single incandescent lamp, a small current will flow, due to the initial electromotive force, and this, flowing round the field magnets a few times, will slightly increase the flux

[redacted]

and the terminal potential difference. A further diminution in the external resistance will lead to a larger current round the field-magnet winding, and a further rise in the terminal potential difference. It will be seen that by reducing the resistance of the external circuit sufficiently, the electromotive force will rise on the magnetization of iron curve, and will have its maximum value when the external resistance is reduced to the minimum, and the maximum current is flowing in the external circuit.

The characteristic of the series machine is shown in Fig. 107,

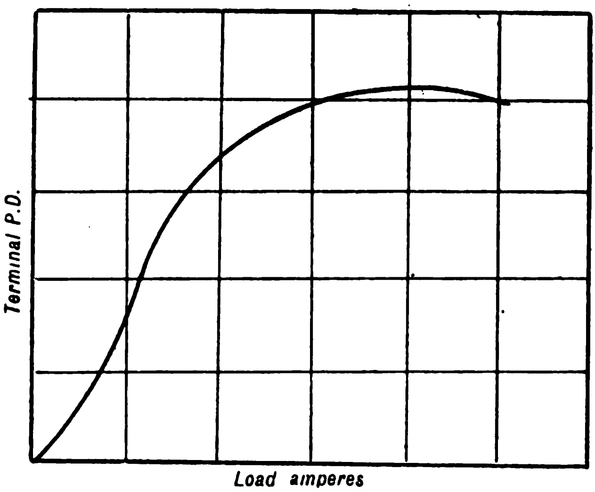

FIG. 107.

and it will be seen that the terminal potential difference varies considerably with changes in the load. It is in no sense a constant-potential machine, but might be called a constant-current machine, for it is only with a constant current that the electromotive force is constant. Its uses are therefore limited to such a case as lighting a group of arc lamps, which are all switched on or off together. On switching on such a group of lamps, the electromotive force will rapidly grow, and the current with it, to its final value, and there remain fixed. On switching off, the current disappears, and with it the excitation and the terminal potential difference.

The effects produced by the series machine will be seen to be opposite to those produced by the shunt. This has led to a combination of the two which automatically compensates for the voltage drop with increasing loads, without the necessity of adjustment by the field rheostat. This will probably be seen best by considering the characteristic for the series machine plotted with external resistance as base (Fig. 108), as was done in Fig. 105 for the shunt machine. With a small resistance in the external circuit, the terminal potential difference and the flux will have maximum values. By increasing the external resistance, the exciting current falls, and finally, the critical point on the bend of the magnetization curve being reached, the magnetization drops at a great rate, and with it the potential difference.

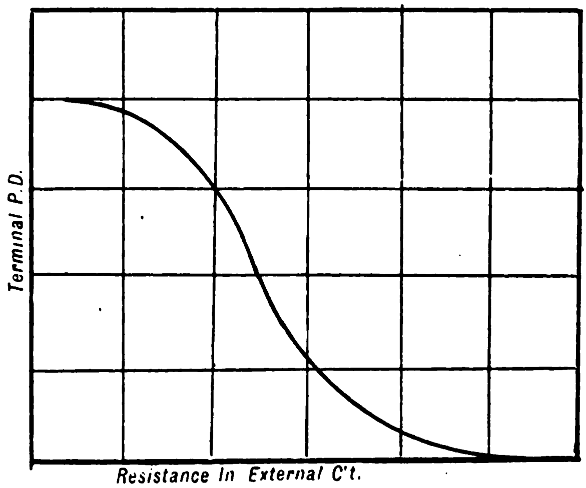

FIG. 108.

Comparing this curve with that for the shunt machine in Fig. 105, it will be seen that the two are approximately opposite in their effects. If the two machines were coupled together and connected in series, the potential difference would be fairly constant for all changes in the external resistance, for if the resistance of the circuit be diminished so as to take a large current, the drop in the shunt machine will be made up by the increase in volts generated in the series machine. There is, however, no necessity for having two machines to do the work

[redacted]

of one. If the shunt machine be provided with both shunt and series winding, and connected as in Fig. 109, we should get the same effect as with the two separate machines coupled.

In this case it will be noticed that fewer series turns will be required than are necessary for the series machine alone, for we have only to make up with them the volts lost in armature reaction and CR drop, and the whole of the current passing through the series winding provides a large additional magnemotive force with relatively few turns. As the flux at full load has to be increased considerably by the series ampere-turns, it is advisable to employ a smaller density in the magnetic circuit at no load, than would be the case with a shunt-wound machine. Owing to the changing permeability of the circuit, the compensating action of the series ampere-turns cannot be made to give very close adjustment of pressure for all loads, and for this reason the

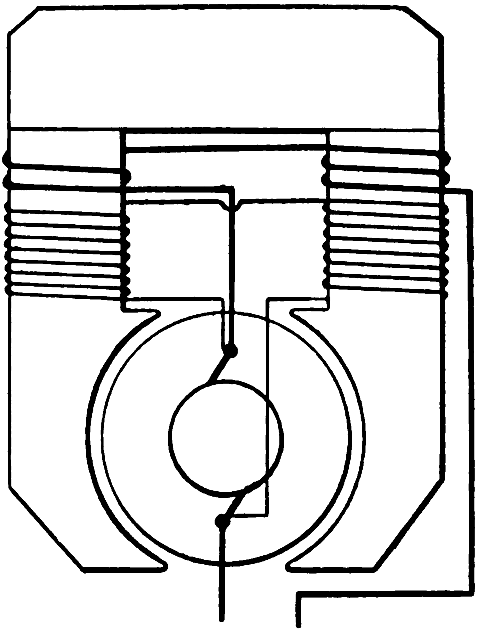

FIG. 109.

[redacted]

separate excitation method, with hand regulation, is preferred where large machines are used for lighting purposes. For power purposes, however, hand regulation is out of the question, owing to the very sudden manner in which the load changes, and the machines have therefore to be compounded as described above.

In the case of the separately excited machine, it was seen to be possible to raise the potential difference with increase in load, and in the compound-wound machine the number of series ampere-turns provided may be such as to raise the pressure so as to maintain an approximately constant electromotive force for all loads at the feeding point. This, known as "over-compounding," can be carried to almost any desired extent, though in practice it is found that a 10 per cent. to 15 per cent. over-compounding is usually sufficient for most purposes. It will be noticed that if the machine be supplying a number of feeders from omnibus bars, the amount of over-compounding will depend on the *total* load, and not on the maximum load on any one feeder, so that in the event of one section being heavily loaded, and therefore requiring an increase in pressure, the over-compounding of the machine may be of little service if the other sections are but lightly loaded.

The series winding, carrying the whole of the current, has to be of thick cable. It is usual to allow a current density of about 800 or 900 amps. per square inch in the series coil, and to facilitate winding, fine-stranded cable is often employed. The insulation on this need not be particularly good, for it has only to withstand the pressure difference between one turn and the next, which is very small indeed, but the insulation resistance of the whole, to the field cores or framework should, of course, be very good.

The shunt winding is of fine wire, with many turns, and usually absorbs $\frac{1}{100}$ to $\frac{1}{200}$ of the total output of the machine. The full potential difference is available for urging the current through the shunt winding, and the exciting current will therefore depend on the resistance of the circuit. For any given number of ampere turns, the smaller we make the current, the larger must be the number of turns, but we are limited in the depth of winding on account of the heat developed, which causes a temperature rise in the coil; this being usually limited to about 40° C. above the temperature of the room. At this steady temperature a balance

[redacted]

is established between the rate of receiving heat (proportional to C^2R), and the rate of losing it. The coils lose heat principally by radiation from their surface, and a little by conduction through the field cores which they surround. The inside layers will therefore usually be much hotter than the outside ones, and from experiments made to test this difference in temperature, it is found that the maximum temperature difference exists in layers about two-thirds of the depth from the surface. For any given temperature rise, therefore, we must provide a certain amount of radiating surface, depending on the rate of receiving heat, *i.e.* on the power spent in the winding. Mr. Esson's rule for the radiating surface required in field magnet coils, wound to a maximum depth of 7 cms., or $2\frac{3}{4}$ inches, is—

$$\left.\begin{array}{c}\text{Required surface of coil in}\\ \text{sq. cms.}\end{array}\right\} = \frac{\text{watts expended in coil} \times 335}{\text{temperature rise in degrees C.}}$$

Of course, with a smaller depth of winding, less radiating surface will be required; and again, if the coil be specially well ventilated by ducts, formed in the winding to allow air to circulate through it, a smaller surface will suffice. But with a given number of ampere turns to be provided, it usually happens that, with a smaller depth, a larger surface is necessary to accommodate the required number of turns. In some cases, but more particularly in the field winding of alternators, very thin copper strip is employed, wound on edge by a special tool, which, after being insulated, is slipped over the core in either a single or double layer only. Being so very thin, the required number of turns can often be got in a single layer, and every turn being equally heated, and all in communication with the outer air, a higher current density can be allowed.

The full-load potential difference of the machine is divided between the two exciting coils, so that the potential difference per coil available will be half that between the terminals. This voltage per coil will be equal to the current in it, multiplied by its resistance,

or volts per coil $= C \times R = C \times \dfrac{l}{\text{sect. area}} \times$ specific resistance

(see p. 7). The length and sectional area being in inches and square inches respectively, the specific resistance is that of an inch cube at the final temperature of the coil. Suppose we allow for a temperature rise of 35° C., then as the resistance varies by 0·428 per cent. per degree rise in temperature, the specific resistance will be increased from the value given on p. 7 to $\frac{0\cdot75}{10^6}$ ohm. We might write this formula in the form—

$$\text{Volts per coil} = \frac{\text{ampere-inches}}{\text{sect. area}} \times \frac{0\cdot75}{10^6}$$

and therefore—

$$\text{Sect. area of winding} = \frac{\text{ampere-inches}}{\text{volts per coil}} \times \frac{0\cdot75}{10^6}$$

A certain winding length having been allowed, and the sectional area of the core determined, the length of a turn in the inside layer, close to the core, is easily calculated. It is as well to allow an inch or so extra, for the wire will probably be wound on a spool, which, together with insulation, will add a little to the length of each turn. Allowing a maximum depth of winding of say 2·75 inches, the length of a turn in the outside layer can also be easily calculated by adding on 2·75 × 2 inches to each dimension of the core. The average or mean length of the turns will then be obtained by taking half the sum of the inside and outside lengths. We can now write for the sectional area of the wire—

$$\left.\begin{matrix}\text{Sect. area in}\\ \text{sq. inches}\end{matrix}\right\} = \frac{\begin{pmatrix}\text{mean length of 1}\\ \text{turn in inches}\end{pmatrix} \times \begin{pmatrix}\text{ampere turns}\\ \text{per coil}\end{pmatrix} \times \frac{0\cdot75}{10^6}}{\text{volts per coil}}$$

From the sectional area, and the table on the following page, the diameter of the covered wire can be found.

The winding length in inches, divided by the diameter of the covered wire, will give the number of turns per layer, and the depth in inches, divided by the diameter of covered wire, will give the number of layers. The product of these two then gives the total number of turns for the coil.

The exciting current is now obtained by dividing the required ampere turns per coil by the total number of turns, and the resistance of the coil, when at its final temperature, by dividing the volts per coil by the current.

[redacted]

S.W.G.	Sectional area of bare wire in square inches.	Diameter of bare wire in inches.	Diameter of covered wire in inches.
000	0·1080	0·372	0·397
00	0·0950	0·348	0·373
0	0·0820	0·324	0·349
1	0·0707	0·300	0·325
2	0·0598	0·276	0·301
3	0·0498	0·252	0·277
4	0·0422	0·232	0·257
5	0·0353	0·212	0·237
6	0·0289	0·192	0·215
7	0·0243	0·176	0·199
8	0·0201	0·160	0·183
9	0·0163	0·144	0·167
10	0·0129	0·128	0·150
11	0·0106	0·116	0·137
12	0·00849	0·104	0·124
13	0·00664	0·092	0·112
14	0·00502	0·080	0·097
15	0·00407	0·072	0·089
16	0·00321	0·064	0·080
17	0·00246	0·056	0·072
18	0·00180	0·048	0·063
19	0·00125	0·040	0·055
20	0·00102	0·036	0·051
21	0·000804	0·032	0·047
22	0·000615	0·028	0·043
23	0·000450	0·024	0·039
24	0·000380	0·022	0·037

The kinetic energy put into the dynamo by the engine is in the main converted into electrical energy in the conductors. There is, therefore, a force on them, or rather on the teeth in which they are embedded, tending to shear them off, which varies directly with the load. When a conductor carries a current at right angles to a magnetic field, there is a force acting on it equal to HCl dynes $= \dfrac{HCl}{981 \times 453}$ lbs., where $H =$ lines per sq. cm., $C =$ current in absolute units, and $l =$ length of conductor in cms. Suppose in a certain case the air-gap density be 6000 lines per sq. cm., the armature 12 inches long, with 100 slots wound with 200 conductors, full load current 500 amps., then the force in pounds tending to shear off the teeth will be $\dfrac{6000 \times 25 \times 200 \times 12 \times 2{\cdot}54}{981 \times 453}$ $= 204$ lbs., and therefore each tooth has to withstand a strain of just over 2 lbs.

[redacted]

In the above formula the current being in absolute units of 10 amps. each, and as each conductor on the armature carries only half the total current in the case of two-pole machines, we get the current per conductor = 250 amps. = 25 absolute units.

We might arrive at the same result in a different way. The horse-power delivered to the dynamo is $= \frac{\text{foot-pounds per minute}}{33{,}000}$ = force in pounds × circumference of the armature × revolutions per minute, divided by 33,000.

Therefore—

$$\text{force in pounds} = \frac{\text{H.P.} \times 33{,}000}{\pi \times \text{diameter} \times \text{revs. per minute of armature}}$$

This, of course, is not quite correct, for the power developed in the armature will be less than that delivered by the steam engine by an amount depending on the efficiency of the machine.

Direct-current machines of the bipolar or multipolar type are frequently run in parallel, *i.e.* two or more supply current to the same set of omnibus bars, from which feeders run to the various feeding points in the supply circuits. The method of connecting a machine in parallel with another one already running is fairly simple. In the case of either separately or shunt excited machines, the speed and excitation are first adjusted till the incoming machine is generating an exactly similar voltage to that of the machines already running under load. It is now switched in, with the positive pole connected to the positive bus bar, and in this condition it is said to be "floating," *i.e.* neither delivering nor receiving current, for its generated no-load voltage is just equal to the full-load potential difference of the other machines. To make it share the load, its excitation must now be increased (see Fig. 110).

If the machine is compounded, we have to guard against a possible source of trouble. Should one machine slow down for any reason, so that its electromotive force falls below that of the bus bars, a current will flow through it from the other machines, but in the reverse direction in the series coil. At a certain point this current will reverse the polarity of the field magnets, and consequently the polarity of the machine, which, on speeding up once more, will then be in series with the bus bars instead of in parallel, and with the added electromotive forces of the two; on

[redacted]

such a low resistance circuit, a burn out must result, unless the machines are provided with overload circuit breakers.

The possibility of such a thing happening is entirely prevented by connecting together the positive brushes so as to form a very low resistance connection between them. This often takes the form of a third bus bar, called an equalizer bar, with a switch for each machine (see Fig. 111), and, in paralleling, this equalizer switch is the first to be put in. In some cases the switches are

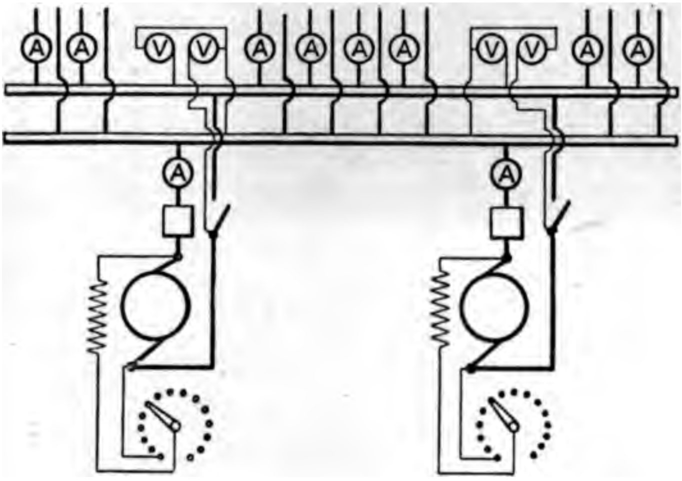

FIG. 110.

interlocked, so that it is impossible to put the machine switch in first or to take it out last.

Should one machine slow down, a current will now flow from the other machines by the equalizer-bar circuit, and through the series coil of the lagging machine, but not in the reverse direction, so that there is now no tendency for a reversal in the polarity. The machine receiving current in this way will run as a motor until, by speeding up, its electromotive force rises again, and it begins to deliver current as before. No serious accident can therefore occur if compounded machines are provided with an equalizer circuit; but it would be decidedly risky to run them in parallel without such a precaution.

With the shunt machine, an equalizer is unnecessary, for whether the machine be delivering or receiving current, the polarity must remain unaltered, for the current in the field winding will flow in the same direction in either case.

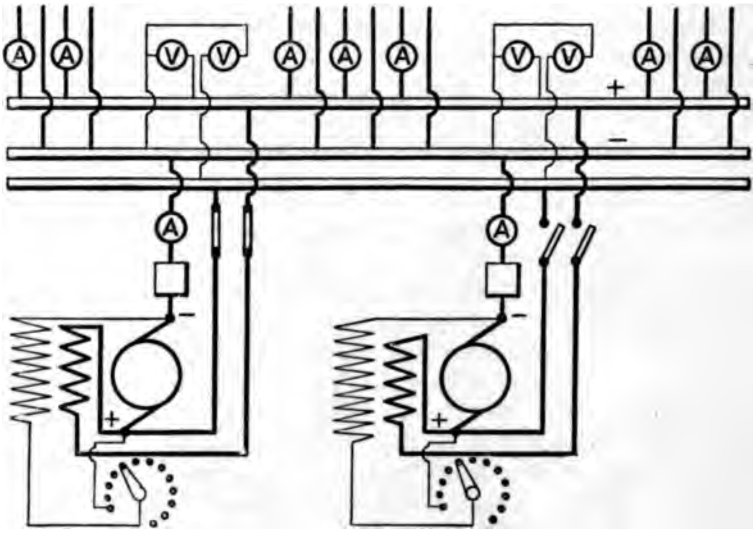

FIG. 111.

CHAPTER IX

BIPOLAR-DYNAMO DESIGN

In designing a machine of any kind, past experience usually plays a very large part. This is particularly so in the case of dynamo machinery. The effects produced by certain modifications being noted, a set of rules and data are soon accumulated, which serve as a guide in future designs.

It should be remembered, however, that it is very seldom that an entirely new design is required. Most large manufacturers have standardized certain lines of machines, of high efficiency and excellent performance, and these usually meet most of the requirements in practice, while any *special* requirement can usually be met with a minimum of expense for new patterns, etc., by a slight modification of some existing design. This applies not only to the two-pole machines we are now considering, but to multipolar direct-current machines and to alternators also.

As we have already seen, a great many points have to be considered if we are to produce a machine which shall be satisfactory in every respect, and as these at times appear to conflict somewhat, a compromise has often to be made.

The design may be commenced from one of several standpoints. A common practice, with two-pole machines, is to first decide on the diameter of the armature, as limited by armature reaction and peripheral speed; then, allowing a certain current density in the conductors, depending on the heating limits and the overload capacity, to find by trial and error the number of slots and the number of conductors per slot.

Let us, by way of illustration, take a 50 kilowatt 200 volt machine, to be either shunt wound, with field rheostat for regulation, or compounded for automatic regulation. This would now be considered a large size for the two-pole type, and though many much larger bipolar machines have been made in the past, most manufacturers would now prefer to supply it as a four-pole

[redacted]

machine. It is proposed in this chapter, however, to deal with only two-pole machines, leaving considerations of the multipolar type for a subsequent chapter.

From the given requirements we have—

$$\text{watts output} = 50{,}000$$
$$\text{volts} = 200$$
$$\text{current} = \frac{50000}{200} = 250 \text{ amps.}$$

Armature reaction limits the largest-size bipolar armatures to something like 2 feet in diameter, and it may be taken that the smaller the diameter the better. We have also to keep in mind the best proportions of diameter and length for whichever type we propose to use. For this size a ring winding would be unsuitable, and with a drum armature, we have seen that the length of core, in the largest sizes, should be about twice the diameter. The correct proportions may be found by choosing a certain diameter, when a little calculation will show whether the value taken is in reasonably good proportion.

The speed will depend on the output of the machine, for the size of the armature depends on the output. The usual speeds for bipolar machines vary between the limits given in the table below :—

From	1·0 to 2·5 kw. . . .	Speed	=	1500 to 2000	revs. per minute
,,	2·5 to 5·0 ,, . . .	,,	=	900 to 1300	,, ,,
,,	3·5 to 13·5 ,, . . .	,,	=	800 to 1000	,, ,,
,,	13·5 to 35·5 ,, . . .	,,	=	650 to 800	,, ,,
,,	35·5 to 70·0 ,, . . .	,,	=	500 to 700	,, ,,
,,	70·0 to 150·0 ,, . . .	,,	=	350 to 500	,, ,,

The speed, however, is often fixed by directly coupling the machine to its engine, in which case it must run at the engine speed. Again, in such special work as turbine driving, the speed often far exceeds the values given in the above table, but in this case a very special construction of both armature and commutator is required.

Taking the diameter of the armature then at, say, 15 inches, we get—

$$\text{circumference of armature} = 15 \times \pi = 47{\cdot}1 \text{ inches}$$

If we now decide to make the width of teeth and slots alike at the periphery, we may take, as a first approximation, $\frac{3}{8}$ inch for the width of slots. We then get—

width of one slot and tooth = 0·75 inch

$$\text{therefore number of slots} = \frac{47{\cdot}1}{0{\cdot}75} = 62{\cdot}8$$

which, of course, will not serve, as we cannot have 0·8 of a slot. We can, however, take either sixty-two or sixty-three slots, and so get the corrected dimensions. With the former figure we have—

$$\text{corrected width of slot and tooth} = \frac{47{\cdot}1}{62} = 0{\cdot}759 \text{ inch}$$

$$\textit{width of slots} = \frac{0{\cdot}759}{2} = 0{\cdot}379 \text{ inch, or practically } 0{\cdot}38 \text{ inch}$$

The depth of the slots, as we have seen, is a point of importance in obtaining sparkless commutation, and if we can limit it to, say, 2·5 times the width, it will be advantageous. In this case we get—

$$\textit{depth of slots} = 2{\cdot}5 \times 0{\cdot}38 = 0{\cdot}95 \text{ inch}$$

$$\text{and therefore } \textit{area of slots} = 0{\cdot}95 \times 0{\cdot}38 = 0{\cdot}361 \text{ sq. inch}$$

$$\textit{current per conductor} = \tfrac{250}{2} = 125 \text{ amps.}$$

The current density allowed in armature conductors is limited by the heating effect only, for the extra voltage drop, due to a higher current density, can easily be made up in the compounding or shunt-regulating arrangements. The space in the armature slots being very limited, the current density is kept high, and usually varies between 1500 and 2500 amps. per square inch. If we allow, say, 2000 amps. per square inch, we get—

$$\textit{sectional area of the conductors} = \tfrac{125}{2000} = 0{\cdot}0624 \text{ sq. inch}$$

We have now to take an approximate value for space factor, and after determining the number of conductors per slot, make the necessary correction. Assuming a space factor of 0·35, we get—

$$\begin{aligned}\text{area of copper in the slot} &= \text{area of slot} \times \text{space factor}\\ &= 0{\cdot}361 \times 0{\cdot}35 = 0{\cdot}1263 \text{ sq. inch}\end{aligned}$$

and therefore—

$$\text{the number of conductors per slot} = \frac{0{\cdot}1263}{0{\cdot}0624} = 2{\cdot}02$$

[redacted]

With two conductors per slot, we get—

$$\textit{corrected space factor} = \frac{2 \times 0{\cdot}0624}{0{\cdot}361} = 0{\cdot}37$$

We have sixty-two slots altogether, and therefore—

$$\textit{total number of conductors} = 2 \times 62 = 124$$

The speed can next be decided upon, and from the table given on p. 141, we find a suitable speed will be, say, 600 per minute. We may therefore take in this case *speed* = 600 *revolutions per minute* = 10 per second.

Applying our formula for the electromotive force, we have—

$$V = \frac{NCS}{10^8}$$

therefore—

$$N = \frac{V \times 10^8}{C \times S} = \frac{200 \times 10^8}{124 \times 10}$$

therefore—

$$\textit{Total lines of force through the armature} = N = 16{,}130{,}000$$

Allowing a maximum magnetic density in the armature core of 16,000 lines per square centimetre, or 103,200 per square inch, the required *sectional area of the iron in the armature core*, taken across a diameter at right angles to the direction of the field through which the whole of the lines must pass, $= \frac{N}{B} = \frac{16130000}{103200}$ $= 156{\cdot}3$ sq. inches. This is exclusive of the depth of the teeth at both top and bottom, also of the space occupied by the shaft and ventilating tunnels, and insulation between the plates.

The diameter of the shaft, obtained by the formula given on p. 105, viz. $d = 7\sqrt[3]{\frac{\text{H.P.}}{R}}$, gives $d = 7 \times \sqrt[3]{\frac{67}{600}} = 3{\cdot}3$ inches at the centre; but, as was pointed out, this gives a very liberal allowance, so that probably 3 inches diameter would be sufficient.

The ventilating tunnels vary in shape. In some cases a series of circular holes, and in others three or four slots or segments, are punched in each plate, so that, when threaded on the shaft, the holes or slots coincide and leave a series of free spaces communicating with the ventilating ducts between the plates. These tunnels practically cut off the metal nearer to the centre, and to be on the safe side it is advisable not to count on that part carrying any of the armature field, especially as the permeability of the shaft will probably be very small compared with that of the core plates.

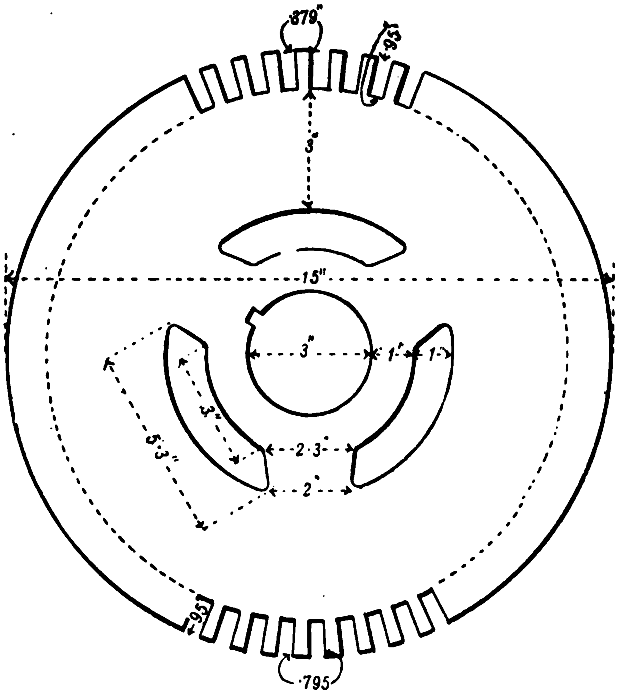

FIG. 112.

From the above considerations we get the dimensions of the armature-core plates, as given in Fig. 112, from which we find the effective depth through which lines of force will pass = 6 inches, and therefore in order to obtain the necessary sectional area the length of iron in the armature measured axially $= \frac{156{\cdot}3}{6}$ $= 26$ inches. The total length of the core will be rather more than this, as the space occupied by the ventilating ducts and insulation must be added to the length of the iron. With this length it would be best to allow four ventilating ducts, each 0·38 inch wide, and adding, say, 10 per cent. for insulation, we get *length of armature* = 30 inches practically.

The density of the lines in the armature will vary from point to point, but the maximum value of 16,000 lines per square centimetre will only be obtained for a short length across a diameter at right angles to the direction of the field. With multipolar machines the density in the teeth is often much higher than in the body of the core, but with two-pole machines the lines spread over practically half the teeth, and the density in them is usually less than in other parts of the core. The *mean* sectional area of the iron in each tooth—the tooth tapering inwards to keep the slot parallel—is equal to the product of its mean width and its length. In our case the figures are $26 \times 0·355 = 9·23$ sq. inches, and therefore in thirty teeth we have a net sectional area of iron of 277 sq. inches, or 1786 sq. cms. If we assume that all the armature flux passes through the teeth, and none across the slots, we have a magnetic density in them of $\frac{16130000}{1786} = 9031$ lines per square centimetre. The *average density* in the armature will therefore be more nearly 12,000 than 16,000; and if we take the former figure, it will probably be near enough, for the length of the magnetic circuit in the armature core forms but a very small proportion of the total, and consequently no very great error would result even in leaving it out of account altogether.

Commutator.—In two-pole machines the whole of the current has to be collected by a single set of brushes, and therefore, in our case, the current to be collected by each line of brushes = 250 amps. This necessitates a certain brush contact area depending on whether we intend using copper or carbon brushes. The former will require a shorter commutator, and will therefore produce a shorter shaft and bedplate, and a less weighty machine, but one with a greater tendency to sparking than if carbon brushes are employed.

The total number of armature turns being small, we can allow one commutator bar to each armature turn, which will be an advantage in giving a minimum reactance voltage, and so aiding in sparkless commutation. In this case, therefore, the *number of commutator bars* = 62.

[redacted]

The wearing depth of the commutator depends somewhat on the discretion of the designer. With carbon brushes the amount of wear is often very small, so that in two-pole machines a wearing depth of $\frac{1}{2}$ inch or $\frac{3}{4}$ inch is usually considered a liberal allowance.

If we allow a wearing depth of $\frac{3}{4}$ inch, the total depth of each segment will require to be about double this amount to allow for the coned supports. We therefore get—

total depth of commutator segments = 1·5 inch

We must allow about 0·25 inch below the bars for insulation, whether it be air or fibre, while the sleeve will require to be at least 0·25 inch in thickness, and may with advantage be raised, say, 1 inch, to give a slightly larger diameter to the commutator, and therefore thicker bars and shorter lugs.

The commutator, shown in Fig. 113, is built up on the shaft with the above dimensions; the shaft being reduced in diameter at this part, forming a shoulder against which the commutator sleeve butts.

The diameter of the commutator works out at $8\frac{1}{2}$ inches. *The circumference of the commutator* = $8·5 \times \pi = 26·7$ inches, and the *circumferential velocity of the commutator* = $2·22 \times 600 = 1332$ feet per minute.

The width of each commutator bar, plus the mica insulation on the face, will be = $\frac{26·7}{62} = 0·43$ inch, and allowing 0·03 inch for the insulation, we get—

width of each commutator bar on the face = 0·4 inch

If we decide to use carbon brushes—which is certainly advisable, from a commutating point of view—each brush, if of the usual type and size, will span 2 bars, and being about 1·5 to 2 inches in length, each brush will have a contact area of 1·2 to 1·6 sq. inches.

Allowing a current density in the brush contact area of 30 amps. per square inch, we shall require $\frac{250}{30} = 8·3$ sq. inches of contact area, and as each brush spans 2 bars, giving a length to the curved surface of the brushes of 0·83 inch, we get,—length of brush contact = 10 inches. With 1·5-inch brushes, this will necessitate 7 brushes per set. The brush holders will be about 1·75 inches wide, and therefore the minimum length of the commutator wearing face will be = $7 \times 1·75 = 12·25$ inches.

[redacted]

The commutator lugs will have to be about 1 inch wide by $\frac{1}{16}$ inch thick, which gives a current density in them of 2000 amps. per square inch at full load, which, owing to the very special cooling due to the whole surface being exposed to fanning action, is quite a reasonable allowance. The commutator sleeve head with insulation will have to be about 1·25 inches in length for this size commutator, while the coned washer and locknuts at the other end will occupy another 2 inches. We might save most of the latter length, however, by undercutting the commutator, as in Fig. 114, and in this case we have—

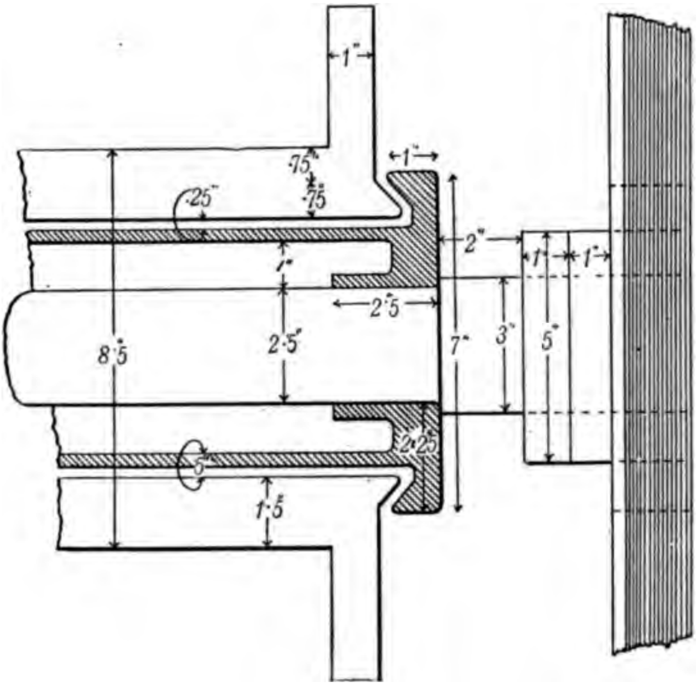

FIG. 113.

$$\textit{over-all length of commutator} = 14{\cdot}5 \text{ inches}$$

We may now make dimensioned sketches of the complete armature, commutator, and shaft, as represented in Fig. 115.

If we employ a barrel winding, which is usual with this size and type, the end connections will each be approximately 26 inches in length, the length of one complete turn will therefore be approximately 112 inches. The resistance of each turn $= \frac{\text{length}}{\text{sect. area}} \times \text{sp. res.} = \frac{112}{0·0624} \times \frac{0·75}{10^6} = 0·00133$ ohm, at the working temperature. The brushes will connect the winding into

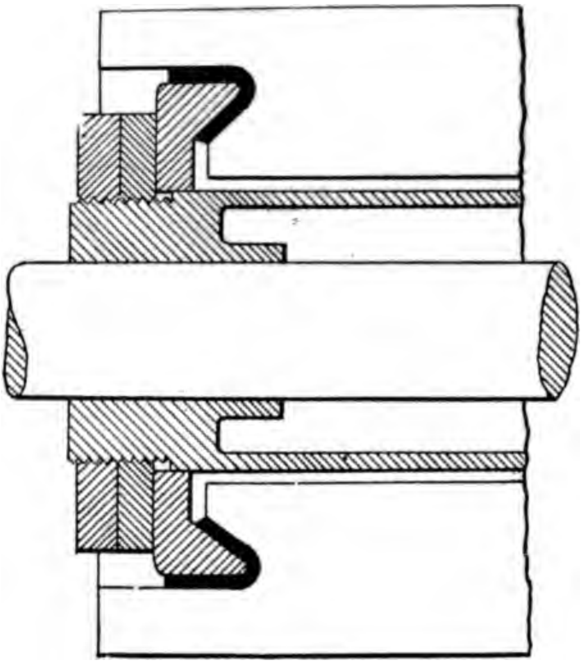

FIG. 114.

two equal parts in parallel, each consisting of 62 conductors, or 31 complete turns, and therefore—

$$\left.\begin{array}{l}\textit{resistance of armature from}\\ \textit{brush to brush}\end{array}\right\} = \frac{31 \times 0·00133}{2} = 0·02 \text{ ohm}$$

$$\textit{the full load CR drop} = 250 \times 0·02 = 5 \text{ volts}$$

$$\textit{full load } C^2R \textit{ armature loss} = 250^2 \times 0·02 = 1250 \text{ watts}$$

In all magnetic circuits magnetic leakage takes place from practically every point. This must be so, for there being no magnetic insulators, the flux produced by the exciting coils divides in inverse proportion to the magnetic reluctance of all possible paths. The total leakage lines at the various points may be calculated separately from certain approximate rules, obtained for leakage from various surfaces; thus, the leakage from two parallel surfaces, as represented by the inside walls of the field-magnet cores, will be equal to—

$$L = \frac{1{\cdot}6 \times (A_1 + A_2) \times E}{D}$$

where $A_1 + A_2$ represents the sum of the areas of the two surfaces, D the distance in inches between them, and E the average number of exciting ampere turns linked with the leakage flux in the area considered. (In the case of the inside walls of the field-magnet limbs, E would be equal to half the total ampere turns, while for portions of the circuit below the coils, such as the horns of the pole pieces, E would be equal to the total ampere turns.)

If the surfaces are in the same plane, as represented by the sides of the field-magnet limbs, then—

$$L = \frac{2 \times (A_1 + A_2) \times E}{D}$$

Taking each part separately and applying the appropriate formula, we can determine approximately the total leakage lines, and adding this to the armature flux, obtain the total flux in the field-magnet limbs.

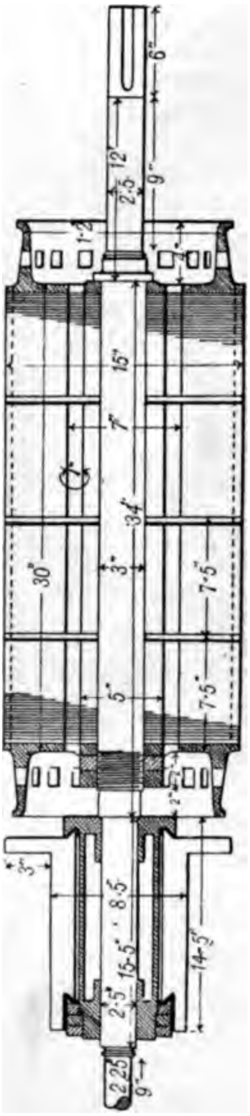

FIG. 115.

This, however, cannot be done till we have decided on the

[redacted]

number of ampere turns on the field-magnet limbs, so that a value for leakage factor has to be assumed in the first place, and modified afterwards if considered necessary. Experience has shown, however, that with a given type, the variations are but small, except that the larger the machine the smaller is the leakage coefficient. For two-pole machines the values will usually be found close to those given below.

For undertype machines—

Up to about 10 kw.	leakage factor	=	1·3
From 10 kw. to about 25 kw.	„ „	=	1·25
„ 25 „ „ 50 „	„ „	=	1·2
„ 50 kw. to the largest sizes . . .	„ „	=	1·15

For overtype machines—

Up to about 10 kw.	leakage factor	=	1·25
From 10 kw. to about 25 kw.	„ „	=	1·2
„ 25 „ „ 50 „	„ „	=	1·15
„ 50 to the largest sizes	„ „	=	1·1

For double magnetic circuit machines of the Manchester type as represented in Fig. 45—

Up to 10 kw.	leakage factor	=	1·35
From 10 kw. to about 25 kw.	„ „	=	1·3
„ 25 „ „ 50 „	„ „	=	1·25
„ 50 kw. to the largest sizes . . .	„ „	=	1·2

Taking a leakage coefficient in this case of 1·2, we get—

$$\textit{total flux in the field-magnet limbs} = 16{,}130{,}000 \times 1{\cdot}2$$
$$= 19{,}356{,}000 \text{ lines}$$

and with a density of 15,000 lines per square centimetre, or 96,750 per square inch, which is about the usual practice, we have—

$$\textit{sectional area of the field-magnet limbs} = \frac{19356000}{96750} = 200 \text{ sq. inches}$$

The axial length of the pole pieces should be a little less than that of the armature core, to allow for the fringing at the ends. If we allow 1 inch at each end, we get—

$$\textit{axial length of pole pieces} = 28 \text{ inches}$$

The axial length of the limbs may be less than that of the pole pieces, and they should also be well rounded at the corners. The latter allows of winding the field spools without sharp bends, and the former gives good support to the spools, which, when wound, are often of considerable weight. If we take the axial length of

[redacted]

the field-magnet limbs at 20 inches, we get the depth of the limbs $= \frac{200}{20} = 10$ inches.

The length of the limbs has to be great enough to hold the field winding without too great a depth, for the heating of the inside layers limits the depth. As we do not know yet how many turns, or the size of wire we shall require, we have to take a trial length and modify it afterwards, if found necessary. Of course a greater length will require more ampere turns; but as this affects only a short portion of the iron part of the circuit, many more turns than are required for the additional length can usually be got on. A length rather less than the diameter of the armature usually suffices for two-pole machines, so that in our case we may take as a first approximation the length of the field-magnet limbs as 12 inches.

The sectional area of the yoke should be greater than that of the limbs, to increase its permeability, and so reduce the tendency to leakage. If we allow an increase of 25 per cent., we get—

sectional area of yoke = 250 sq. inches
magnetic density in the yoke $= \frac{19356000}{250} = 77{,}400$ lines per sq. inch
= 12,000 lines per square centimetre

The circumference of the field-magnet bore covered by the two field-pole faces is usually about 240° or 250° in bipolar machines (see p. 76), which gives a ratio of pole arc to pole pitch of 66 per cent. with the former, and 69 per cent. with the latter.

The length of the air gap may now be fixed. From the curve given on p. 123 a length of 0·5 cm. (= 0·196 inch) will be about suitable for this size machine, giving a length rather more than half the width of the slots. With this value we get—

diameter of the field-magnet bore = 15·39 inches
circumference of field-magnet bore $= 15·39 \times \pi = 48·35$ inches
length of curved surface of pole piece $= \frac{120}{360} \times 48·35 = 16·11$ inches
sectional area of the curved surface of pole face $= 16·11 \times 28 = 451$ sq. inches
= 2909 sq. cms.

The effective area of the air gaps, allowing for the spreading of the field, will be obtained by enlarging the area of the curved surface of the pole face by 0·8 times the length of the air gap all round. This is equivalent to adding 1·6 times the length of the air gap to each dimension, which gives us—

effective area of the air-gaps = $(16 \cdot 11 + 0 \cdot 313)(28 + 0 \cdot 313)$
= 465 sq. inches
= 3000 sq. cms.
magnetic density in the air gap = $H = \frac{16130000}{3000} = 5376$ lines per square centimetre
total length of air gaps = 1 cm.

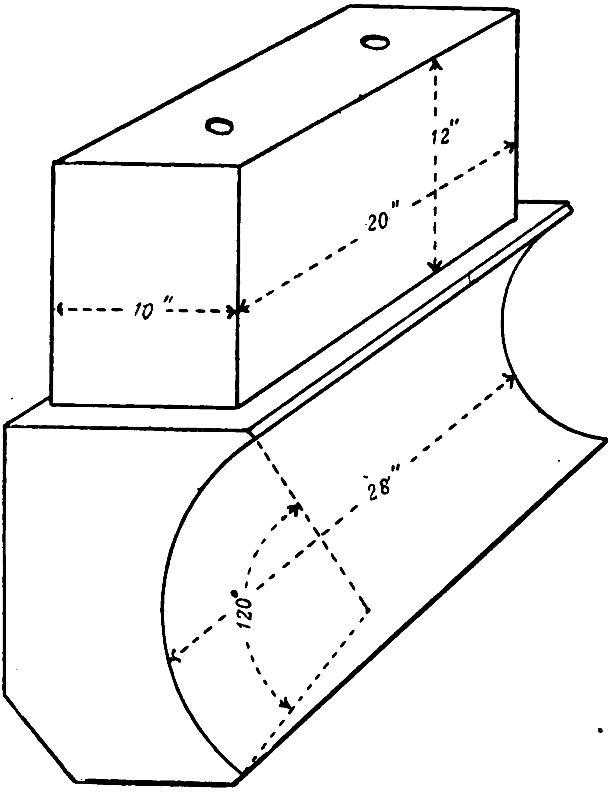

FIG. 116.

We have now to estimate approximately the mean length of a line of force in the field-magnet limbs, yoke, pole pieces, and in the armature. It should be remembered that no great error will result by taking only approximate lengths in the iron portion, for an extra inch or so, more or less, makes but a small percentage difference in the total ampere turns required, owing to the high permeability of the iron compared with that of the air-gaps. Slight inequalities in the permeability of the iron, and air-films at the joints, often make more difference than would be made by an extra few inches in the unbroken length of iron. With this in mind, we may take the various lengths as given in the sketch (Fig. 117).

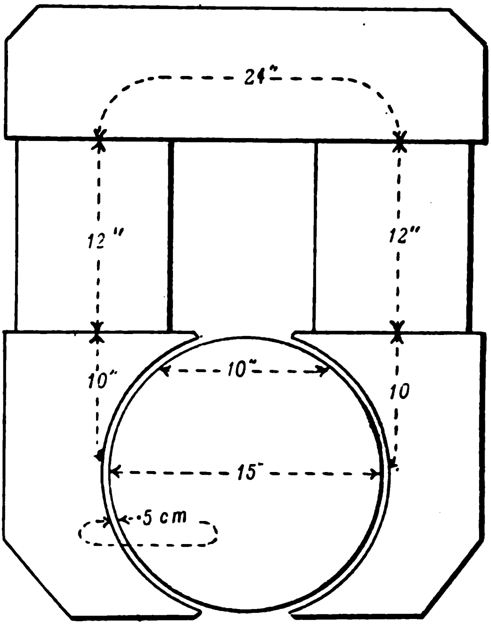

FIG. 117.

From the magnetization curve given on p. 25 we can read off the ampere turns per centimetre length for each portion at its respective density, and these, together with the other data just found, can be entered in a table, as given on the following page.

[redacted]

Sectional areas.	Length of mean line.	Value of B.	Ampere turns per cm.	Total ampere turns.
Limbs = 200 sq. ins. = 1290 sq. cms.	24 ins. = 61 cms.	15,000	25	26×61 = 1586
Yoke = 250 sq. ins. = 1612 sq. cms.	24 ins. = 61 cms.	12,000	7	7×61 = 427
Pole face = 451 sq. ins. = 2909 sq. cms.	—	—	—	—
Effective air gaps = 3000 sq. cms.	1 cm.	H = 5376	0·8×H = 4300	4300
Armature = 156 sq. ins. = 1000 sq. cms.	10 ins. = 25 cms.	12,000	7	7×25 = 175
Pole pieces = 400 sq. ins. = 2580 sq. cms.	20 ins. = 50 cms.	7,500	3	3×50 = 150

The total ampere turns for the no-load electromotive force of the machine will therefore be = 6638. It will be noticed, in passing, that the ampere turns required for the pole pieces and armature form but a small percentage of the total.

With the usual brush position, as explained on p. 116, we have the total number of conductors in the angle between the pole tips = $\frac{60}{360}$ of 124 = 20, and therefore the total number of turns acting as demagnetizing turns will be = 20.

The current carried by these turns at full load will be = 125 amps., so that *total demagnetizing ampere turns* at full load = 20 × 125 = 2500, which must be counteracted by additional exciting ampere turns.

The full-load volts drop in the armature we have found to be 5 volts, and this also must be made up by additional ampere turns, so as to provide a larger flux at full load. The additional lines and ampere turns at full load are found in a similar manner to that just employed; but it must be remembered that the ampere turns per centimetre are not those required for the extra lines simply, but those required to change the density from the no-load to the full-load value. Going through the same process, we have—

$$\text{full-load volts drop} = 5 = \frac{\text{NCS}}{10^8}$$

$$\text{therefore N} = \frac{5 \times 10^8}{124 \times 10} = 40{,}3200 \text{ additional lines in the armature at full load.}$$

[redacted]

The full-load armature flux will be increased from 16,130,000 to 16,533,200.

The maximum density in the armature will therefore be increased at full load to $\frac{16,533,200}{156} = 106,000$ per square inch, or 16,434 per square centimetre.

In the air gaps the density is also increased, for the increased armature flux has to pass across them. The density in the air gaps at full load $= \frac{16533200}{3000} = 5511$.

Adding on 20 per cent. for leakage, the full-load additional flux in the limbs and yoke will be $403,200 \times 1{\cdot}2 = 483,860$, making a total of 19,839,800 lines.

The density in the field magnet limbs at full load $= \frac{19839800}{1290}$ $= 15,380$ lines per square centimetre.

The density in the yoke at full load will be $= \frac{19839800}{250} = 79,350$ per square inch, or 12,300 per square centimetre.

Neglecting the armature and pole-pieces, we find from our magnetization curve the extra ampere turns per centimetre for the additional density at full load to be—

For the field-magnet limbs . .	6 per centimetre.
„ „ yoke . .	2 „
„ air gaps.	108 „

Total additional ampere turns to provide—

For the limbs	$6 \times 61 = 366$
„ yoke	$2 \times 76 = 152$
„ air gaps	$= 108$

Therefore for the CR drop at full load we require 626 additional ampere turns, and an additional 2500 to counteract the back magnetization, making a total of 3126 additional ampere turns at full load.

The no-load ampere turns we found to be 6638, and therefore we require 9764 amp. turns at full load.

The full electromotive force of 200 volts will be available for the exciting circuit, and this, according to Ohm's law, will be equal to the current in it, multiplied by its resistance when heated to its final temperature, or, $200 = C \times R = C \times \frac{l}{sa} \times$ specific

[redacted]

resistance. For a temperature rise of 35° C. the specific resistance of copper is increased to $\frac{0\cdot75}{10^6}$; therefore—

$$200 = \frac{\text{amp. inches}}{\text{sec. area}} \times \frac{0\cdot75}{10^6}$$

The mean length of one turn of the winding can be found approximately by taking a certain depth, say 2·75 inches, which is found by experience to be about the maximum depth to allow for the usual temperature rise of 35° C. The mean length of a turn will then be equal to the sum of the lengths of an inside and outside turn, divided by two. In our case, the length of an inside turn will be = 60 inches, plus 6 inches, say, to allow for the space occupied by the body of the spool with insulation, while the length of an outside turn will be 82 inches, so that the mean length of the turns on each bobbin will be $= \frac{66 + 82}{2} = 74$ inches.

The electromotive force on the ends of each bobbin will be equal to half the total, or = 100 volts, and we require 9764 ampere turns for the two, therefore 4882 for each bobbin.

$$\text{Therefore } 100 = \frac{\text{ampere inches per spool}}{\text{sect. area}} \times \frac{0\cdot75}{10^6}$$

$$\text{,,} \quad 100 = \frac{4882 \times 74}{\text{sect. area}} \times \frac{0\cdot75}{10^6}$$

$$\text{Therefore sect. area} = \frac{4882 \times 74 \times 0\cdot75}{100 \times 10^6} = 0\cdot0027 \text{ sq. inch}$$

From the table given on p. 136, it will be seen that the nearest gauge wire is No. 17, with a sectional area of 0·00246 sq. inch, and a diameter, covered, of 0·072 inch. Where great accuracy is required, and the size wire does not work out to any particular gauge, it may either be specially drawn, or appropriate lengths of the two nearest gauges may be taken and jointed. If we take this gauge wire, however, and allow, say, 1 inch for the end cheeks of the spools, and $\frac{1}{3}$ of the remaining space for series winding we can get, in one layer, $\frac{7\cdot3}{0\cdot072} = 100$ turns, and in a depth of 2·75 inches, we get 38 layers, so that we have allowed space for 3800 turns on each limb. The full-load ampere turns

[redacted]

per field spool are to be 4882, and therefore the full-load exciting current will be $\frac{4882}{3800} = 1·28$ amps.

The resistance of the shunt winding (hot) will be $\frac{200}{1·28} = 156$ ohms, or 78 ohms per coil.

At no load, the total excitation required is 6638 amp. turns, or 3319 per coil. The no-load exciting current will therefore be reduced to $\frac{3319}{3800} = 0·87$ amp., the resistance of the circuit then being $= \frac{200}{0·87} = 229$ ohms. The resistance of the field rheostat will therefore be $229 - 153 = 74$ ohms, when at its final temperature. This is usually divided up into a large number of sections, and connected to a multiple-contact switch.

The watts spent in the field winding per coil at full load $= 1·28^2 \times 78 = 128$, and the surface area of each coil $= 656$ sq. inches, and therefore the watts per square inch of surface $= 0·2$, which is a very low figure, and indicates that we have allowed more winding space than necessary. The machine would therefore be improved somewhat by altering this dimension, and making the appropriate changes. With 0·3 to 0·4 watt per square inch we should still be within the temperature limit usually found, and this would probably be obtained with field magnet limbs of, say, 9 inches in length (see p. 151).

The reactance voltage worked out by Mr. Hobart's method, as explained on p. 113, gives—

Total length of embedded portion of armature winding per turn } = 152 cms.
Total length of free portion of armature winding per turn } = 81 cms.
Total number of turns short-circuited by one line of brushes } = 2
Peripheral speed of the commutator = 266 ins. per sec.
Width of the curved surface of each brush = 0·83 inch
Current collected per line of brushes = 250 amperes

$$\text{Frequency of commutation} = \frac{266}{2 \times 0·83} = 160$$

$$\left.\begin{array}{l}\text{Inductance of short-}\\ \text{circuited coil}\end{array}\right\} = L = \frac{(152 \times 4 \times 2) + (81 \times 0·8 \times 2)}{10^8}$$

$$= 0·000013 \text{ henry}$$

$$\text{Reactance voltage} = 2\pi n \text{LI} = 6{\cdot}28 \times 160 \times 0{\cdot}000013 \times 125$$
$$= 1{\cdot}6 \text{ volts}$$

The various losses can now be calculated approximately, but the method of doing this will be explained in connection with multipolar dynamos in Chapter XI. The losses are of two kinds: (1) those that do not vary with the load, and (2) those that are proportional to the load. Of the first kind we have:—Watts lost in hysteresis and eddy currents in the armature core; watts lost in bearing and air friction; watts lost in commutator brush friction; and watts lost in excitation. The variable losses include the armature and commutator C^2R losses.

The efficiency for any load is then determined approximately thus—

$$\text{Efficiency in per cent.} = \frac{\text{output}}{\text{output} + \text{losses}} \times 100$$

[redacted]

CHAPTER X

MULTIPOLAR-DYNAMO CONSTRUCTION

EXPERIENCE has shown that for large powers a modification in the design of the two-pole type of machine is desirable. Above, say, 100 or 150 kw., the commutating troubles in collecting the large current with one set of brushes, and the very large armature reaction concentrated, as it were, on one pair of poles, makes sparkless running difficult. Not only this, the size and weight of the field-magnet system and the unwieldy size of the field-magnet bobbings become excessive with the only methods of support applicable, to say nothing of the cost of such forgings, which rises enormously with the larger sizes. Magnetic leakage also becomes excessive, and the space occupied by the machine is considerably increased. Altogether it may be taken that for large sizes the distribution of the material in a two-pole type is not good, and therefore there is a waste of material which is unnecessarily increasing the weight and expense of the machine. This has led to the introduction of a type of machine having a number of pairs of poles connected together by a common yoke ring, the commutator having a pair of brush sets to each pair of poles, alternately connected in parallel. This is therefore equivalent to a number of small machines built into one, with the effects of armature reaction, etc., subdivided, making sparkless commutation much easier, also giving a much better distribution of the materials.

Figs. 118 to 120 show designs for typical multipolar machines. In Fig. 118 only two coils are provided, though it is intended for a four-pole machine. This is effected by connecting the coils up so as to produce similar poles as shown (see p. 20). The field then completes the magnetic circuit by the easiest path, which will be very largely by the inwardly projecting pole pieces at the top and bottom, which are therefore consequent poles. There being no magnetomotive force on these poles to assist in urging the flux through them, there is a greater tendency to magnetic leakage, and with ordinary parallel winding with four circuits and two pairs of brushes there would probably be sparking at the commutator at full load, owing to different electromotive forces being induced in the various windings. Such an arrangement is only serviceable with series armature winding (to be explained later) with only two brushes and two parallel circuits, and is used largely in this way for traction motors; the design being specially suitable owing to the small space occupied in the vertical direction, which allows of its being fixed in the restricted space under a car. A better arrangement for a four-pole dynamo is that shown in Fig. 119, where each pole is provided with a similar field coil. For larger numbers of poles it is usual, for mechanical convenience, to make the yoke ring in two parts bolted together as shown in Fig. 120.

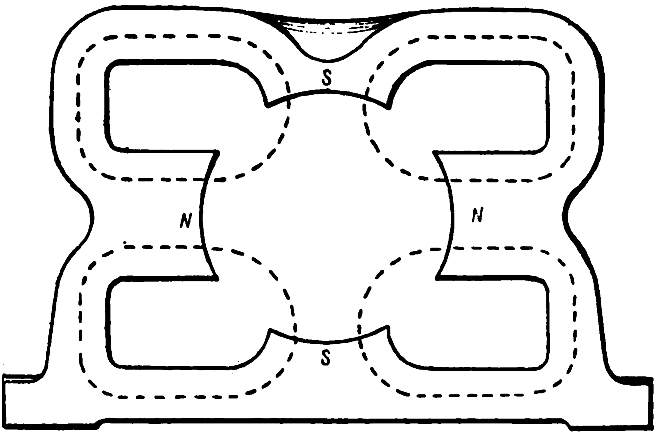

FIG. 118

Multipolar machines of this type, designed for a terminal potential difference of 500 to 550 volts, and over-compounded 10 per cent. to 15 per cent., are employed in many modern power stations, similar machines being used in several lighting stations also, in which case they are usually separately excited by auxiliary plant. The selection of the kilowatt capacity of such machines depends partly on the station output, on the nature of the demand —*i.e.* whether there will be frequent intervals of very light load

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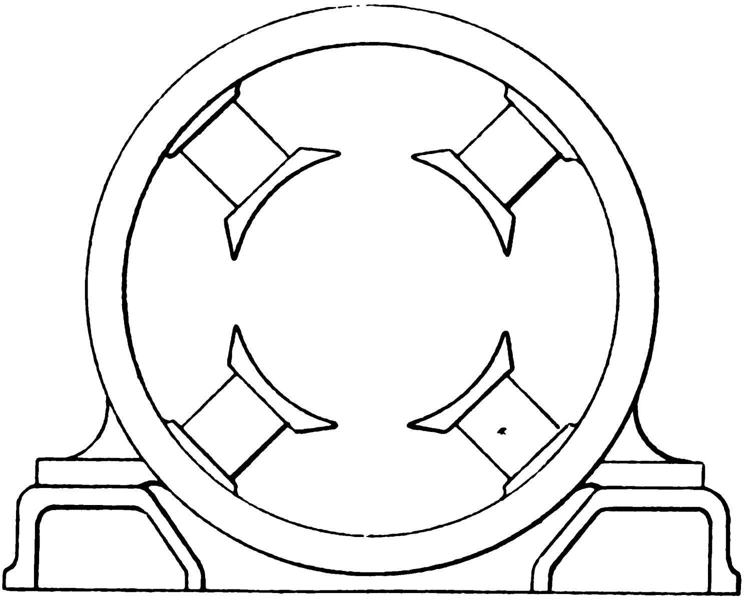

FIG. 119.

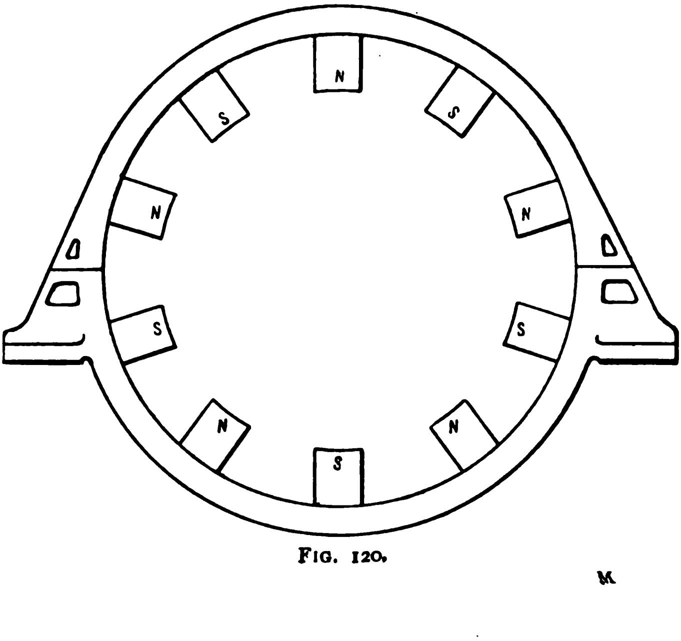

FIG. 120.

[redacted]

—and also on the judgment of the consulting engineer as to the most economical size.

There is a decided advantage in choosing standard machines, for not only are they cheaper—the manufacturer having in many cases purchased or made special machine tools for turning out the various component parts both cheaply and quickly, and the cost of patterns, labour, etc., on a large number of similar parts being much less than on the same number of parts, each differing in some detail—but in case of breakdown a new part can be supplied from stock in a very much shorter time than would be possible if the machines were specially made from an original design. Again, the manufacturer may be relied upon to have made exhaustive tests and experiments on each particular machine, and brought it to a high degree of perfection for the type in hand before going to the outlay of special plant, whereas it often happens that an entirely new machine requires a certain amount of modification before it is perfectly satisfactory in every respect.

Fig. 121 represents a standard modern multipolar direct-current traction generator, made by the "English Electric Manufacturing Company," now Messrs. Dick Kerr & Co.

The manufacturer has to consider methods of reducing the cost of construction to a minimum. If he makes machines of the same output for lighting and traction at varying voltage, he arranges as far as possible that the same framework, bedplate, shaft, bearings, pedestals, etc., may be employed for a number of different machines. In many cases the patterns are made adjustable in width, so as to suit various voltages.

For small current and high voltage the armature core and the field magnet must be wider to develop the higher electromotive force, but the commutator may be narrower, while for the reverse requirements, viz. low voltage and large current, the armature and field should be made shorter, while the commutator, to deliver the larger current, should be made longer. Thus a large range of machines of varying voltage may be made by the same special machinery by making the patterns adjustable in width.

The field-magnet cores are often made of wrought iron or steel, circular in section, bolted to the yoke ring. The circular section has the advantage that the amount of copper required for

[redacted]

any given number of field turns is less than with any other section. In other cases the cores are made of laminated sheet steel, riveted together, and cast-welded into the yoke ring. These usually approximate to a square section. Cast steel being so commonly

FIG. 121.

employed in dynamo building, the poles are sometimes cast in one piece with the yoke ring, and pole shoes of cast iron or laminated sheet steel bolted on after the coils are put in position.

One important advantage attending the use of laminated poles lies in the fact that, when the machine is compounded, they respond much more rapidly to the variations in the compounding current, for the rapidly changing current causes eddy currents in solid poles which prevent a very rapid change in the flux, while if laminated these eddy currents are practically absent, and the machine is therefore much more responsive to rapidly changing loads. It is for this reason that many of the large compounded traction generators are provided with laminated poles.

Where the pole cores are made of solid wrought iron or cast steel it is distinctly advantageous to laminate the pole surfaces, for the sweep of the field across the face due to the armature teeth gives rise to eddy currents, which cause heating of the face and undue loss. The eddy currents are considerably less in cast-iron pole shoes than in wrought iron, owing to the higher specific resistance of the former. With laminated poles, undoubtedly the best method of fixing them to the yoke ring is to cast and weld them together, though several other methods are adopted. A common method is to punch them with a square hole near the centre, into which, after building up and riveting together, a square

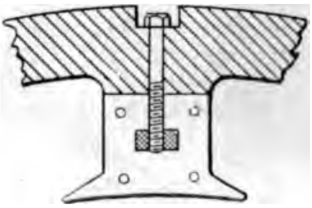
FIG. 122.

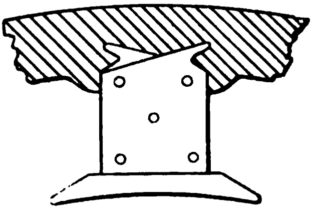
FIG. 123.

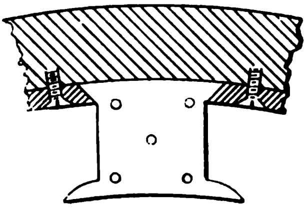
FIG. 124.

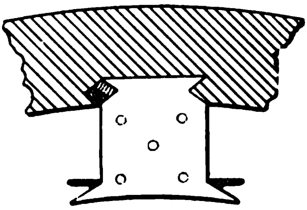
FIG. 125.

[redacted]

bar of iron or steel is inserted, and a bolt passing through the yoke ring into this bar holds it in firm contact with the yoke ring, the contact surfaces being, of course, carefully machined up. Another method is to stamp them with bevel-edged projections at the root, by which they are clamped to the yoke ring with special steel clamps, while others dovetail the ends of the cores, fixing them into corresponding dovetailing in the yoke ring by means of steel keys. These various methods of support are illustrated in Figs. 122 to 125.

FIG. 126.

Where laminated cores are employed, the plates are usually about $\frac{1}{8}$ inch in thickness. A sufficient number of these are placed one above the other till the requisite sectional area is obtained, four or more holes having previously been punched in each plate. Two heavy cast-iron, or steel, end-plates are then put one on either side, and the whole riveted together. When the cores are to be cast-welded to the yoke-ring, the top ends of the plates are left rough; and in some cases are punched into a dovetail, so as to take a better grip of the cast iron (Figs. 123 and 126).

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The method of casting the yoke-ring with laminated poles is very clearly shown in Fig. 127. A mould is prepared in the foundry for half the yoke-ring, and the required number of field

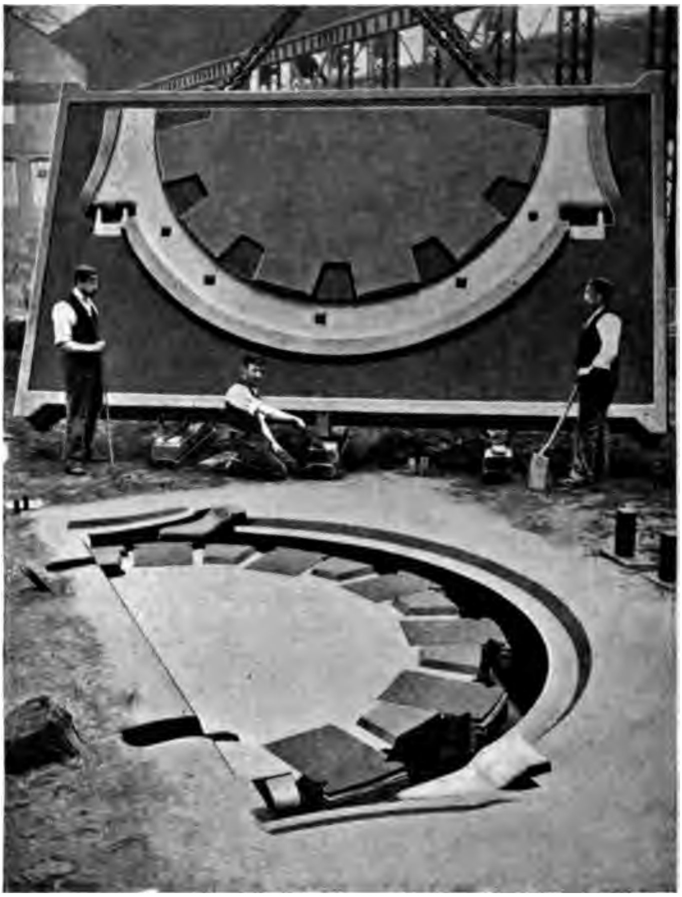

Fig. 127.

cores are inserted in the mould. The cover, seen in the background, having been carefully lowered into place by means of a travelling crane, the molten iron or steel is poured in through the openings seen at the side; vent holes being made in the cover to allow the air to escape. The illustration shows the mould for casting the lower half of the yoke-ring, provided with the frame support, and pockets for bolting it to the upper half, which is cast in the same manner, but without these supports.

The castings so made are allowed to remain in the mould for several days untouched, so as to cool very slowly. This ensures the limbs and yoke being well annealed, making them easier to machine up, and also procuring the highest permeability obtainable.

The two halves of the magnet frame are now carefully machined and surfaced on the faces that are to be united, and the parts are then bolted together by four stout bolts in the inwardly projecting pockets. In some cases lugs are made on the top and bottom castings, by which the two parts are bolted together.

The two supports are planed up perfectly square with the plane of the field-magnet ring, and four steps, which have been cast on one side of the frame—two on each half—are now surfaced up, and four bracket arms, intended to support the brush-rocker ring, bolted in position. The whole is then mounted on a special boring machine, which turns both the inner faces of the field cores and the brush-rocker brackets at the same time, thus ensuring that the brush gear shall be perfectly concentric.

The field coils are wound on bobbins, and in some cases are ventilated by allowing space between the core and the inside of the bobbin. The finished coils are of considerable weight, and have to be firmly supported. A common practice is to make the flanges of the bobbin of light brass castings, ribbed to increase their strength, and riveted to a sheet iron or steel body, as shown in Fig. 128. In other cases the bobbin flanges are made of some insulating material, and the weight is taken by the pole pieces or pole shoes. The shunt winding usually consists of double cotton-covered wire, shellac varnished on each layer as the winding proceeds, and where the machine is compounded, the thick series turns are usually wound as a separate coil, occupying about one-third of the total winding space of the bobbin. The series and shunt coils are then joined together by clamping connectors.

Armature cores are built up on a massive cast-iron spider, rigidly keyed to the shaft, or, in some cases, fixed by steel rings shrunk on. In the latter case the arms are cast disconnected at the boss, as in Fig. 129; while in the former they are usually disconnected at the periphery, as in Fig. 130. This is found to be necessary in the larger sizes, for, if cast in one piece, great strains

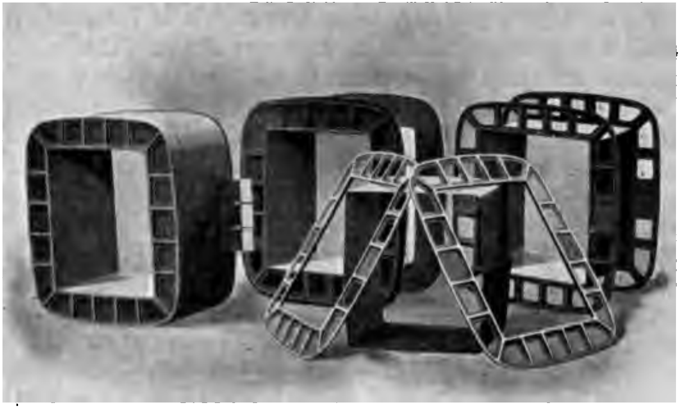

Fig. 128]

are imposed on it in cooling, due to the thinner portions solidifying and shrinking before the thicker portions. This straining is entirely avoided by leaving the arms free.

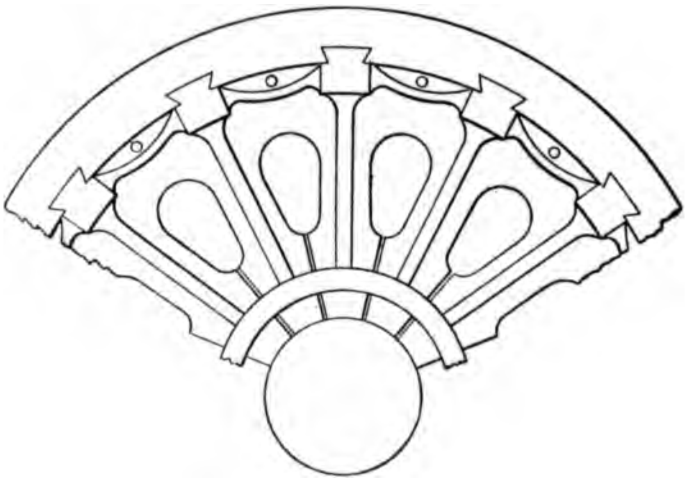

Fig. 129.

The spider illustrated in Fig. 130 is supported on the shaft at the ends of the boss only, the centre portion being cored out. This saves a large amount of time and expense in machining. The outer edge is cast into a series of dovetails, which are machined to fit corresponding dovetailing in the armature core plates. This, together with the end clamping-plates, gives a very good mechanical support, and allows free access of air to the under sides of the plates, which assists very materially in keeping the armature cool. The spider is first mounted in the lathe, and the hub turned to a very accurate fit on the shaft. The outer edge is turned at the same time, and also the face, or the hub, to which the commutator spider is to be fixed. If it is to be connected to the shaft by keys, the keyways are next cut.

FIG. 130.

The armature core is built up of sheet-steel stampings, with

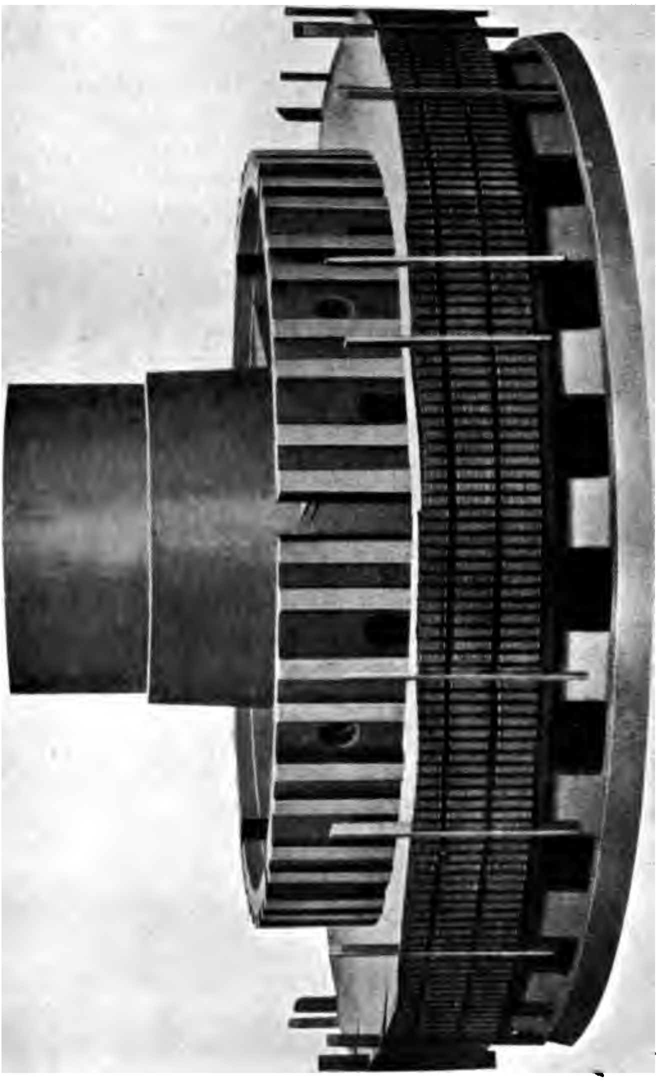

Fig. 131.

slots punched in their outer edges, and keyways or dovetails to fit the spider on the inside. These are wide enough to span at least two of the dovetail supports, and are built up so that the joints overlap. The stampings are first thoroughly annealed, and then varnished on one or both sides. The method of building up the core is very clearly shown in Fig. 131, which illustrates the construction of machines made by Messrs. Dick Kerr & Co. A massive cast-iron end-plate, having a perforated flange for supporting the end connections of the armature winding, is arranged horizontally on a suitable floor, and the armature spider lowered on to it and arranged perfectly concentric. The

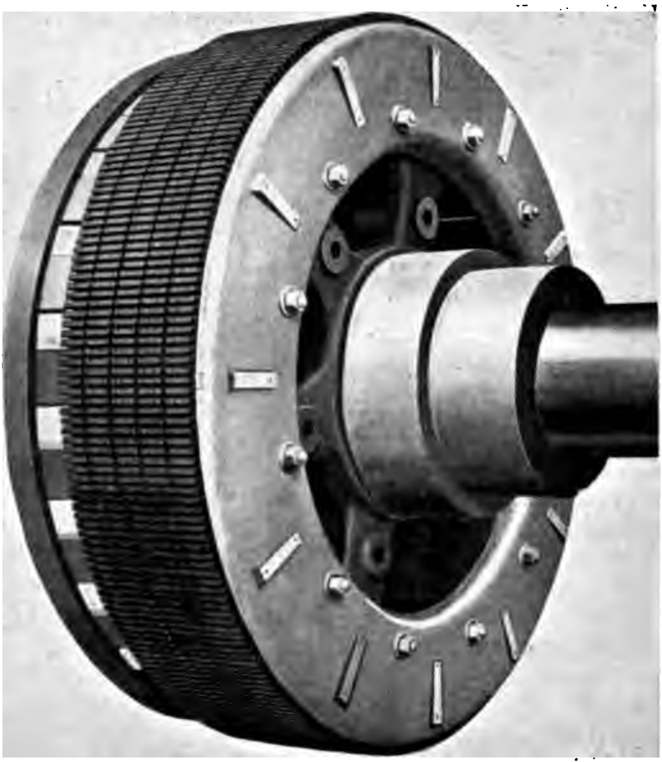

FIG. 132.

core segments are then threaded on by slowly going round the spider, every layer overlapping the joints in the one below. After a depth of about 3 inches has been so obtained, special ventilating segments (see p. 80), with the teeth twisted through 90°, are threaded on, and at intervals, depending on the size of the machine, a number of segments slightly smaller in depth are employed for a thickness of about half an inch, to allow for binding wire, where such is employed for keeping the armature conductors in place. A similar number of stampings are now threaded on as before, and then other ventilating sections, and so on till the required depth is obtained. A second massive end-plate is now lowered on top of the segments, and the whole bolted firmly together by a number of steel bolts, which pass through between the under edge of the core plates and the face of the spider. The completed core is shown in Fig. 132.

The commutators of these machines are built up on a separate cast-iron spider (seen in Fig. 121), and keyed to the hub projecting from the armature spider. This ensures the commutator being perfectly concentric, and is a common practice, though the shape and method of fixing varies slightly. Fig. 133 shows the same as applied by the International Electrical Engineering Company, in which the armature hub is shortened, and the commutator spider fixed to it by a series of bolts. In some cases, more especially in smaller sizes, the commutator sleeve consists of a flanged cast-iron ring, bolted all round to facings turned near the outer edge of the armature spider, as shown in Fig. 134.

The number of commutator bars depends on the size of the machine and the number of poles. In almost all of the larger sizes we have the minimum number of armature turns per bar, to keep the inductance of the coils as low as possible. Usually there are between fifty and sixty bars to each pair of poles, which necessitates a commutator fairly large in diameter. The method of supporting these on the commutator sleeve varies considerably. In almost every case the sleeve is turned on its surface, and a solid, insulating support provided for the underside of the bars. The segments are insulated with mica, and usually fixed between mica-coned rings and bolted up with a clamping ring, in a similar manner to that described with two-pole machines (p. 85). Where the lugs are extra long, trouble has been experienced in some cases by them breaking off, due to vibration and expansion and contraction. To minimize this the lugs are sometimes made with a deep bend or buckle near their centre, to render them more elastic. With long commutator segments, often running at a high peripheral speed, there is a great tendency for the bars to bulge

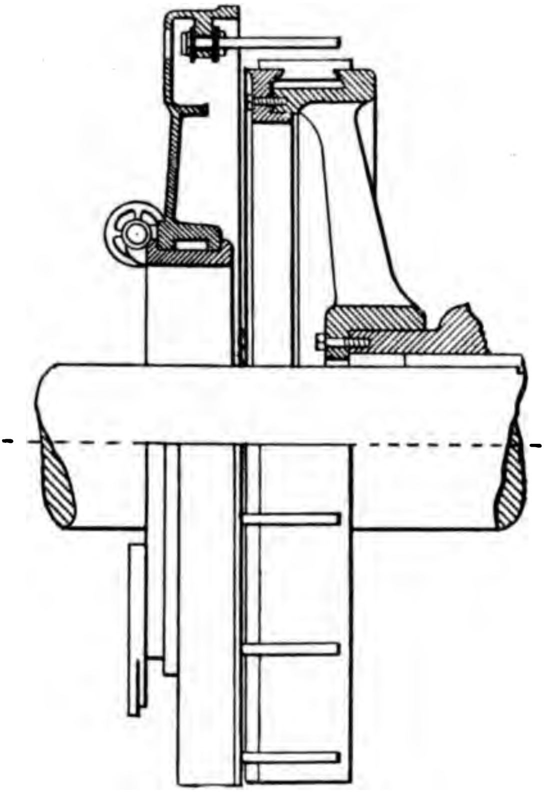

FIG. 133.

outwards by centrifugal action. Special arrangements are sometimes found to be necessary, such as using bars drawn so as to interlock, as shown in Fig. 135. One bar then supports another. These are built up and pressed home in the hydraulic wheel-press, and turned for the end supports, as explained in connection with commutators for two-pole machines. Fig. 136 shows the component parts of a commutator, including also the commutator built up ready to be fixed on the armature hub seen in Fig. 132. It will be noticed that the inclined supporting edges are, in this case, cut deeply. This allows a longer commutator face than in the case where the supports come farther out. The wearing depth for machines of this size is usually about 1 inch.

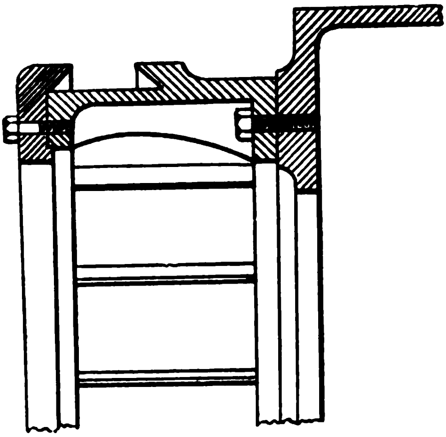

FIG. 134.

Barrel winding is almost exclusively employed in large multipolar machines, as this interferes least with the ventilation of the core, and all parts revolving at the same circumferential speed, the maximum cooling effect is obtained. The coils are also easily formed, and the space occupied by the end connections is less than in other windings.

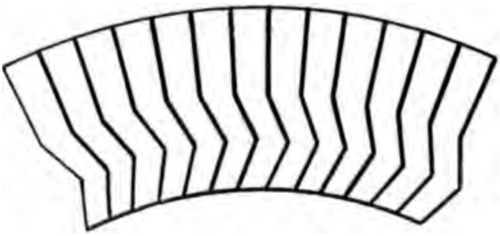

FIG. 135.

[redacted]

Two different methods of connecting are commonly employed, known as "lap" and "wave" winding. These are illustrated diagrammatically in Figs. 137 and 138, the difference being in the direction in which the ends of the coils are taken in connecting to the commutator segments.

All that has been said with regard to drum windings in

FIG. 136.

Chapter VII. for two-pole machines applies also to the multipolar type. For lap winding the number of conductors must be even and divisible by the number of poles. The number of slots and commutator segments must also be even. Both front and back pitches must be odd, and differ by two. The average pitch should not be very far from the total number of conductors divided by the number of poles, *i.e.* must not be shortened too much. A lap winding for a six-pole machine is shown in Fig. 139, where the front pitch is 9, and the back pitch 7.

A great variety of different windings may be made for special requirements, though, in the main, we find these reduced to but one or two for most machines.

Where high electromotive forces are required, a wave winding may be employed, sometimes spoken of as "series" winding. In this case only two sets of brushes are necessary for any number of pairs of poles, and there being only two circuits in parallel, each conductor carries half the total current of the machine. More than two brushes may be used with this winding, but in this case the special advantages attending its use are lost, and better results can be obtained with lap winding. With "series" or "wave" winding the number of commutator segments must be odd if the number of pairs of poles be even, and *vice versâ*. The front and back pitches must be odd, and may either be alike or differ by 2. The average pitch must be

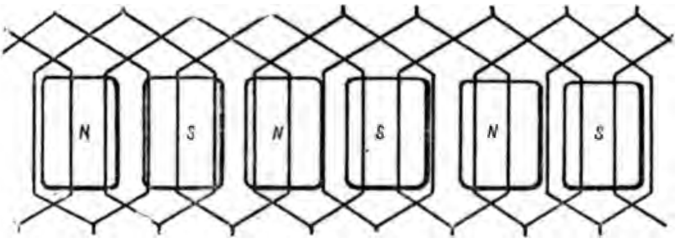

FIG. 137.

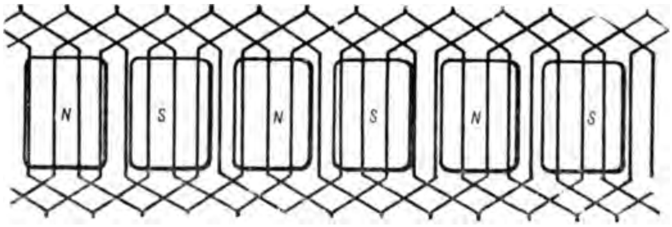

FIG. 138.

$$= \frac{\text{total number of conductors} \pm 2}{\text{number of poles}}$$

Fig. 140 shows a wave winding, from which it will be seen that the pitch is continuously forward.

With lap winding there is a tendency to sparking, owing to

[redacted]

inequalities in the current collected by each set of brushes. With series winding and a single pair of brushes the current in each must be alike, as in an ordinary two-pole machine, while any want of equality in the various magnetic circuits has practically no effect, for there must always be exactly the same electromotive force generated by the two sides of the winding. If, for instance, a little wear at the bearings causes inequalities in the length of the air gaps, or if there be slight differences in the magnetic quality of the iron of the various magnetic circuits, the air-gap densities will differ, even when excited with the same number of ampere turns. Each half of the winding will, however, have just the same number of conductors in both the stronger and weaker field at the same time, and must therefore generate the same electromotive force. For small-sized four-pole machines, where the current to be collected can easily be managed with one pair of brushes and a commutator of reasonable length, this winding is very successful.

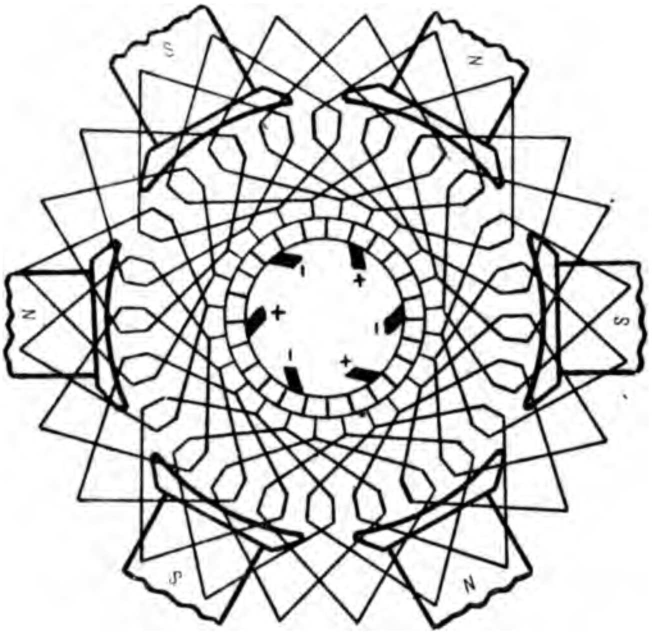

FIG. 139.

[redacted]

Four-pole machines of this type, series wound, are used very largely as motors for traction work. In this case, owing to the wear allowed at the bearings, there is often a measurable difference in the air-gap lengths, which makes series winding almost indispensable. The work of trimming brushes is also reduced, and the pressure (usually 500 volts) is distributed over a larger proportion of the total armature conductors, compared with the same machines when lap wound, where the full potential difference exists on ¼ the total conductors.

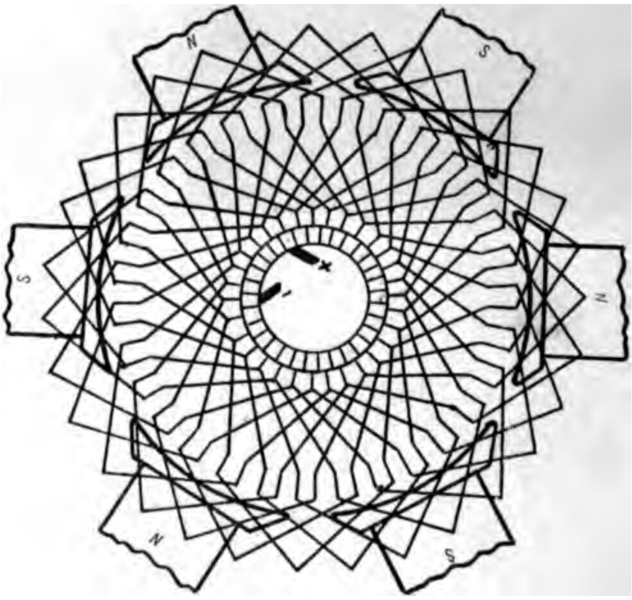

FIG. 140.

In some machines, a combination of the two types of winding, invented by Professor Arnold, and known as the Arnold series-parallel winding, is used. In this the number of slots and commutator segments must be even, and there are as many sets of brushes as poles, alternately positive and negative. After going completely round the armature, the conductor ends, ***not*** at a commutator section next to the one started from, as in Fig. 140, but at one farther in advance. A specimen of this winding for an *eight-pole* machine is shown in Fig. 141.

Where exceptionally large currents are to be collected, a modification in the winding is sometimes made, known as duplex, triplex, or multiplex winding. With this, two, three, or more separate and distinct windings are employed, in no way connected, except by the brushes on the commutator segments. Imagine two separate closed windings on the same armature core. It is evident that these might be connected up to two separate

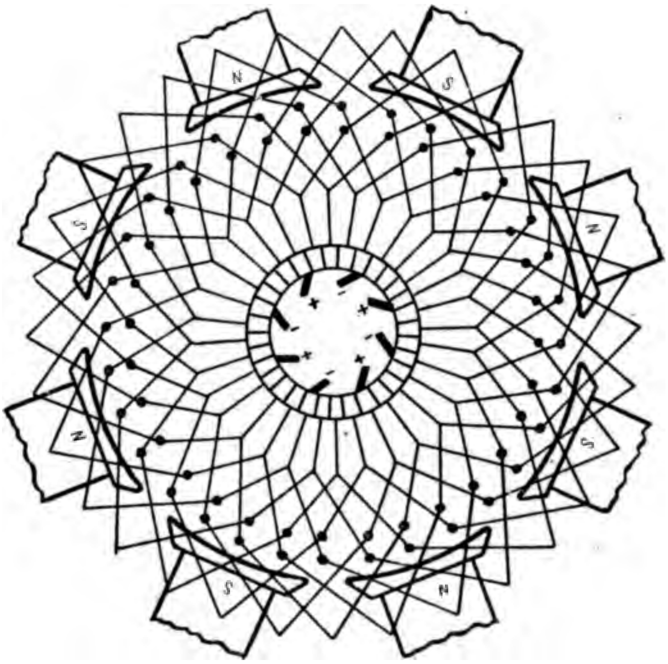

FIG. 141.

commutators, from which two similar-strength currents may be collected. The electromotive forces being exactly alike, the two may be put in parallel if required. But the two commutators might be built in one by connecting the windings to alternate bars all the way round. A commutator bar of the first winding would then be separated from the next bar of the same by a bar connected to the second winding, and if the brushes be wide enough to span two bars, the two sets of winding will be in parallel, and

[redacted]

will supply equal currents to the brushes. In a similar manner we may have three or four separate windings connected up to every third or fourth commutator bar, with brushes wide enough to span the whole. A duplex winding is shown diagrammatically in Fig. 142.

The great advantage of this method of winding lies in the splitting up of the large current into two or more smaller ones, thus reducing the reactance voltage per turn, and making it easier to obtain sparkless commutation. There may also be some saving in the labour of winding, and less chance of eddy currents in the conductors, by their being smaller in sectional area.

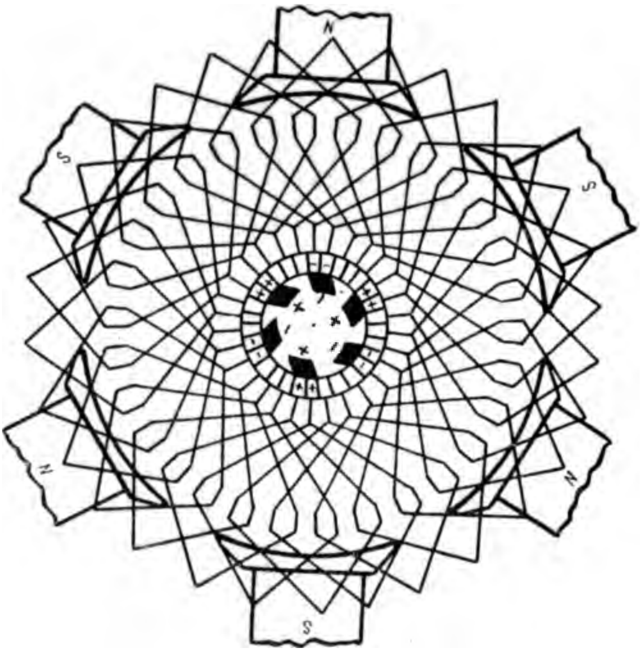

FIG. 142.

On the whole, it may be taken that the plain, simple, lap winding, shown in Fig. 139, is most suitable for the great majority of machines, and only in special cases is it desirable, or at all *necessary*, to employ any other winding.

[redacted]

A common practice with ordinary lap winding is to cut bare copper strip, of the requisite sectional area, into lengths sufficient for one turn each. These are bent on edge at the centre, so that the two halves lie flat, edge to edge, the bending being done in a special machine. The two legs are then further bent on a former, hexagonal shaped, so that the two free ends, in crossing, form an angle opposite the edgewise bend. In this way all coils are alike and interchangeable, so that in case of accident, a new one can be replaced from stock with a minimum of time and trouble, there being no joints, except at the commutator lugs.

Each coil is now carefully insulated with special insulating material, in some cases consisting of a mica composition. They are then taped and immersed in insulating varnish, and baked in a drying oven. For high pressures this dipping and baking process is repeated two or three times. In some cases machines are employed for winding on the tape, but with practice it is done very quickly and effectively by hand. The varnish employed should be waterproof and elastic; many varieties get very brittle after some time, and should a coil or coils have to be removed for any reason, the risk of cracking the insulation in so doing is very great.

Half as many coils as there are conductors per slot are then bound together with tape into one, except at the crossed ends leading to the commutator; thus, if there are to be six conductors per slot, then three single turns will be bound together to form one armature coil, but with six free ends. These are now placed in the slots, after the latter have been examined, and any sharp projections filed down. One limb of each coil goes to the bottom of the slot, with a strip of insulating material, such as micanite cloth, or presspahn round it, the other leg standing above the slots. After going once round the armature, so as to get one leg of each coil to the bottom of the slots, the second leg is similarly insulated and pushed in place on top of the bottom legs. In this way one limb of each coil is at the bottom, and the other at the top of a slot all the way round, producing a perfectly symmetrical winding. Should it become necessary to replace a coil at any time, the old one can be removed by levering up the few overlapping coils at the top of the slots, which are again dropped in place after the new one has been fixed in position.

Where the conductors take the form of thick copper bars, the usual practice is to make each complete turn in two parts (Fig. 143). These are bent to the three-sided shape of the half coil, and the connection, at the end remote from the commutator, is made after the conductors are in place, by binding them together and soldering also, for not only must the electrical connection be perfect, but the joint must be able to withstand any force arising from the conductors tending to move circumferentially as they rotate.

With multipolar, parallel-wound armatures we have to guard against any inequality in the magnetic circuits. It is exceedingly difficult to ensure all the magnetic circuits being exactly alike, for a blow-hole in a casting or slight differences in the iron or in the joints will cause variations in the permeability sufficient to produce varying eletromotive forces, while any want of equality in the length of the air gap will have a very marked effect. For this reason equalizing rings are usually employed, *i.e.* rings to which conductors that should be equal in potential are connected. A conductor facing a north pole in, say, the mid-pole position, should be at the same potential as all other similarly situated conductors on the armature, and therefore, if connected to a common conductor or ring, no current should flow through the conductor. If, however, there be a difference of potential in the conductors so connected, currents will flow in the equalizing rings to equalize the potential, which might otherwise give rise to sparking at the commutator. We might, therefore, have as many such rings as there are conductors between any pair of poles, but *such a large* number is by no means necessary, six to ten being

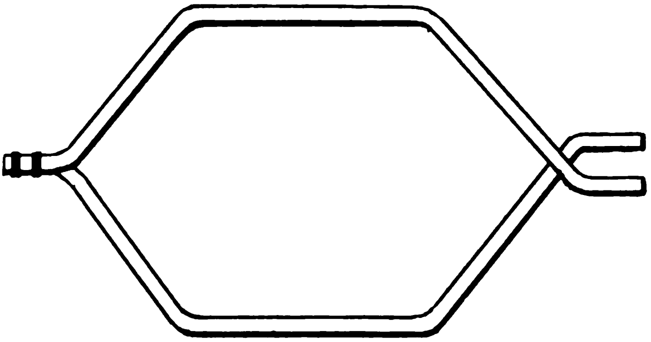

FIG. 143.

sufficient for even the largest sizes. These are usually clamped in insulators at the back of the commutator on to small steps cast on the armature end plate, as seen in Fig. 132, and connection is made to each from the commutator segments at as many points as there are pairs of poles.

The brush gear varies considerably, and is usually made to have a certain amount of adjustable movement round the commutator, though this is scarcely necessary in modern machines, seeing that sparkless commutation for all loads with fixed brushes is a *sine quâ non* with most specifications. The two chief methods of supporting the gear are illustrated in Figs. 121 and 133, that shown in Fig. 121, illustrating the brush gear of Messrs. Dick Kerr & Co., being the more common.

In this a ring of inverted channel section is cast in two halves, so as to be easily removable without disturbing any part of the machine. As many grooves as there are poles are cast in the outer edge to take the brush holders, the covers for these being cast separately and bolted on. Four supporting segments, two on each half, are also cast on the side of the channel ring, and two additional bosses are provided to support the main cables which connect the brush-holders. The two halves are machined and bolted together through flanges cast on for the purpose, and the supporting segments are then turned true so as to move easily within four bracket arms attached to the field-magnet frame (see Fig. 144).

Inside the channel two cables are clamped on insulating supports. Each cable has a number of stout copper strip connections jointed to it, equally spaced round, so as to make connection to every alternate brush-holder, and is taken right round the ring. The two ends, after being brought outside, are sweated to a common thimble for securely attaching it to the terminal board fixed to the bottom of the field frame. By this method of wiring we have a double connection to each brush, and therefore should a break occur in either cable at any point there will still be a perfect connection to the brushes.

The brush-holder frames for these machines are made of brass, and are insulated from the cast-iron ring by an ebonite sleeve and large ebonite washers. These are clamped in the recesses cast in the edge of the ring and fixed by means of bolts, which also clamp the cable connections, the latter being bent

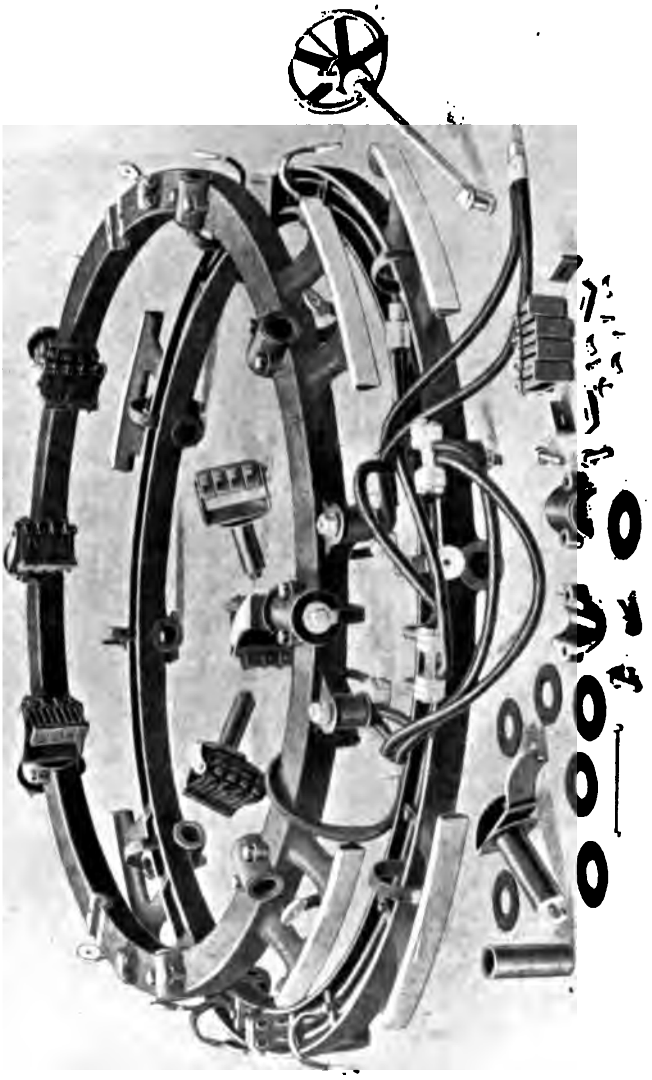

FIG. 144.

round, clear of the cast-iron ring. These frames are wide enough to take four or more brush-holders, depending on the size of the machine.

The brush gear is placed in position between the supporting bracket arms, with the channel facing the field frame, and a small amount of rocking is provided for by a hand-wheel turning on a screwed spindle attached to the end of one of the projecting supporting segments of the brush ring. The hand-wheel has a nut attached, the latter being free to revolve in a supporting bracket bolted to the side of the field frame, and is kept in position by a pin passing through the bracket and into a groove turned near the end of the nut-spindle. The lower end of the steel rod which screws into the hand-wheel is attached to the brush ring by a bolt passing through an enlarged head embracing the supporting segment, thus allowing freedom of movement in the plane of the ring.

In cases where the brush-rocker ring is carried by a bracket bolted to the bearing, as in Fig. 133, it is entirely independent of the yoke ring; but, on the other hand, there is a greater chance of its being slightly eccentric in respect to the commutator. In this case the yoke ring is perfectly free to be unbolted so as to lift the upper half, or the whole to be racked sideways to inspect or repair an armature or field coil without disturbing the brush gear.

With the former method of support—*i.e.* by brackets from the yoke ring—the machine is more self-contained, so that it may be coupled directly to the engine with or without the outer bearing, and this seems to be the method mostly preferred. The racking of the field frame can easily be arranged for in the direction toward the commutator, and therefore the brush gear need not be disturbed in so doing.

Copper brushes for multipolar machines are almost things of the past, owing to the superior commutating properties of carbon brushes, as explained on p. 118. With the extremely rapid and heavy fluctuations met with in traction work it would be very difficult to run these generators with copper brushes without heavy sparking at times, which would soon tell seriously in the cost of keeping the commutator in fair condition, to say nothing of the cost of brushes.

There is practically no difference in brush-holders for

[redacted]

multipolar machines compared with those for two-pole machines, and all that has been said in this connection on p. 92 applies also to multipolar machines. With the latter, however, it is perhaps a more important point, seeing that the number employed in a single machine is often very large. Take, for instance, a machine with eight pairs of poles and, say, ten brushes per set. This gives 160 brushes and separate brush-holders in the machine, and as these form one of the very few parts which are handled by the station attendant, it is of the utmost importance that they be as perfect in design as is possible. Besides, the sparking properties of a machine may be enhanced by employing an inferior type of brush-holder, and it is scarcely good policy to risk the reputation of a machine by such a small item as the brush-holders.

It has been pointed out in connection with two-pole machines that armature reaction produces a field in the leading pole tips opposed to the field of the magnets, which is, therefore, weakening the main field at these parts, while at the receding pole tip the field is strengthened by the addition of the armature flux. This is exactly the same in the multipolar machine, as will be seen by considering the direction of the armature cross field. To obtain sparkless commutation at full load, it may be necessary to advance the brushes so that the coil short-circuited by the brush may be in a reversing field.

Many attempts have been made to overcome this effect, with more or less success, as explained in Chapter VIII., one of the most successful being to so saturate the pole tips by the main flux that their permeability is very low, and therefore the reluctance of the armature field circuit correspondingly high. This minimizes the armature cross field, and therefore the necessary movement of the brushes to bring the short-circuited coils into a reversing field is considerably reduced, and with a low reactance voltage is in many cases sufficient even for fixed brushes.

Commutating poles have also been applied to multipolar machines to assist in sparkless commutation with fixed brushes, as explained on p. 120, and what has been said there in this connection applies more particularly to multipolar machines.

Mr. Sayers has designed machines so that the brushes, instead of requiring a lead at full load, may actually be permanently fixed with a lag, which thus counteracts the back magnetizing effect of

[redacted]

the armature, and obviates the addition of counteracting ampere turns on the field magnet. This result is obtained by making the connection to the commutator pass through a slot or slots in advance, thus inducing in the short-circuited coil an electromotive force which reverses the current in it, even though the coil itself may be still in a field tending to prevent reversal.

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CHAPTER XI

MULTIPOLAR-DYNAMO DESIGN

IN considering the design of multipolar machines, it will perhaps be best to work out the approximate dimensions as we proceed for a machine of intermediate size, say, a 400 kw. 550 volt machine.

As with the bipolar machine, designers depend largely on past experience, for though theory guides them in obtaining formulæ for most of the points to be considered, yet it is only by experience that really good designs are evolved, and once these are obtained and standardized, it is rarely that an entirely new design is required.

A perusal of the data supplied by various makers shows that in many respects machines for a given output are very similar, varying only in the minor details, though it is but a few years since great variations existed in almost every point. We may therefore conclude that the superiority of the present type of multipolar design has been proved by experience.

Mr. Kapp gives a formula for approximately determining the general proportions, and similar formulæ are given also by Mr. Esson, Mr. Scott, and others. These rules can only be taken as providing preliminary over-all dimensions; machines excellent in every respect vary somewhat from the values given by these formulæ. Kapp's formula is stated thus—

$$\text{kw. output} = \frac{KD^2LS}{10^6}$$

where K is a constant, depending on the output and speed, or what is called the "specific output," *i.e.* $\frac{\text{watts output}}{\text{revs. per minute}}$; D is the diameter of the armature and L its length along the shaft, both in inches; S is the speed in revolutions per minute. In the above formula the values of K usually employed are—

Specific output $= \frac{\text{watts output}}{\text{revs. per minute}}$	K.
125	21·8
250	27·2
375	29·5
500	31·8
625	33·5
750	35·0
1,000	36·3
1,500	38·1
2,000	39·0
3,000	39·1
5,000	39·3
10,000	39·8

Mr. Scott's formula is very similar, viz.—

$$\text{watts output} = KD^2LS$$

where values of K are given thus—

For machines of 500 to 1000 kw. . . K = 0·033
„ „ 300 to 500 „ . . K = 0·03
„ „ 150 to 300 „ . . K = 0·025
„ smaller sizes . . . . K = 0·018

The number of poles depends on the output of the machine. We have seen that the maximum kilowatt capacity per pair of poles is limited to about 150, a figure which might be reduced with advantage, not only to sparkless commutation, but to weight and distribution of materials also. This is, to a certain extent, independent of the voltage, except that for low voltage, and therefore large currents, the number of poles might be increased with advantage, for with a greater number of poles we have more pairs of brushes, and therefore a smaller current to collect per brush.

Mr. Hobart has pointed out, in a paper read before the Institution of Electrical Engineers, that as machines for the same output are alike in the energy transformed, whatever the voltage may be, it would seem feasible to use the same bedplates, pedestals, bearings, and shafts for all voltages. The higher the voltage for any given output the less will be the current to be collected, and therefore the commutator segments may be narrower. This is shown very

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clearly in the three machines (Fig. 145), designed by him to illustrate this principle.

With a commutator of given diameter the maximum number of segments is obtained by making them of the least practicable thickness. This gives the smallest number of ampere turns per segment when a coil is short-circuited by the brush in the act of commutation, which, as we have seen, is of the first importance in determining the sparkless commutating properties of the machine, and should always be made as small as possible.

In the low-voltage machine, the necessary radiating surface for dissipating the heat evolved in transmitting the large current is the limiting factor, and this again varies with the diameter of the commutator, therefore the same diameter commutator should suffice for all voltages.

The axial length of the commutator for the high-voltage machine will be less, for a smaller number of brushes are required, thus leaving more space for the armature in which to develop the higher electromotive force. The extra slot space can then be devoted to greater insulation.

From the foregoing considerations it will be seen that 100 kilowatts per pair of poles would be a reasonable allowance. Taking this value in our case, we find the machine will have $\frac{400}{100} = 4$ pairs of poles, *i.e.* 4 N. poles and 4 S. poles arranged alternately. The current to be collected by the brushes will be $\frac{\text{watts output}}{\text{volts}} = \frac{400000}{550} = 728$ amps. As there will be also 4 pairs of sets of brushes, or 4 positive and 4 negative sets, the current per line of brushes will be $\frac{\text{total current}}{\text{pairs of brushes}} = \frac{728}{4} = 182$ amps. The brushes will divide the armature conductors into 8 parallel circuits, each generating 550 volts and delivering 91 amps., or half the total current collected by any one line of brushes.

The number of revolutions per minute is frequently determined by the speed of the engine, which is usually directly coupled to the machine. If not, we may arrive at a safe value by considering the maximum circumferential speed of the commutator. This should not exceed 2000 or 2500 feet per minute, which is regarded as about the limit in good practice (though higher values are met with occasionally) from the fact that, at speeds much above this figure, the heating of the commutator, due to brush friction,

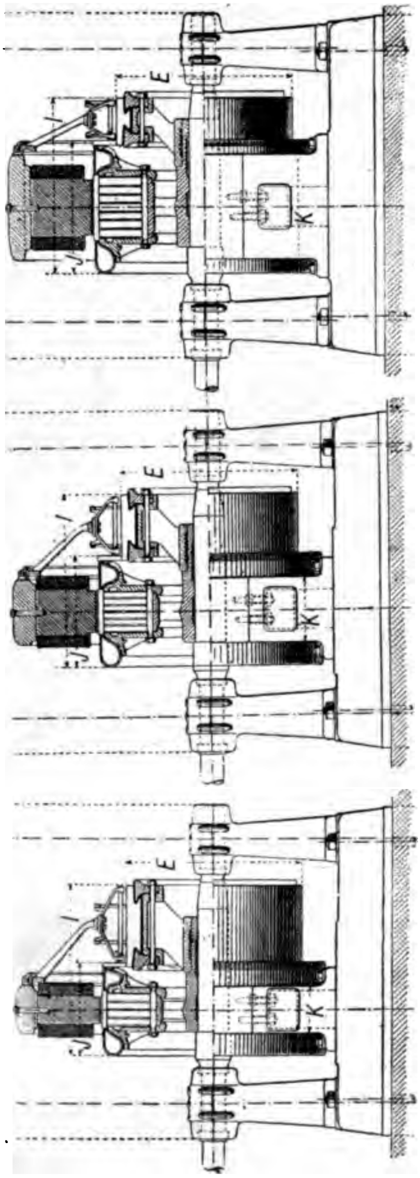

Fig. 145.

becomes excessive, and centrifugal force at the commutator periphery (proportional to the *square* of the velocity) tends to throw out the commutator bars, or cause them to buckle, unless some special device is employed for securing them, such as explained on p. 173.

The brushes will short-circuit at least three commutator bars, and therefore it is best to make the number of turns per bar not greater than one, each turn being joined in series with the next by the connection to the commutator lugs.

The commutator bars must be massive enough to carry the current, and wide enough on the outer face to provide the necessary contact area. The latter might be accomplished by making them long and thin, with more brushes per set; but this would take up more axial space than desirable, involving a longer shaft, etc., and, again, by so doing the commutator would be mechanically weak, with a great tendency for the bars to bulge and possibly fly out.

As a reasonable value, we may allow, as a first approximation, 0·25 inch for the width of each commutator bar at the face, and 0·03 inch for the mica insulation between one bar and the next, in which case we get 0·28 inch width per commutator bar. Between any two adjacent brushes there will exist the full potential difference of the machine, while the voltage between any two adjacent bars must not be too high. If we allow an average of 5 volts per section, we have $\frac{550}{5} = 110$ bars from brush to brush, and therefore 880 in the complete commutator. Taking this number *pro tem.*, the revolutions per minute will be 2000 (feet per minute) divided by the circumference of the commutator in feet, or equal to $\dfrac{2000}{\dfrac{880 \times 0{\cdot}28}{12}} = 97{\cdot}4$, or, say, 100 revolutions per minute.

If we allow one complete turn, *i.e.* two armature conductors per commutator bar (the smallest possible number), we get $880 \times 2 = 1760$ conductors on the armature face. Each conductor will have to carry a current of 91 amps., and at 2000 amps. per square inch the sectional area of each conductor will be $\frac{91}{2000} = 0{\cdot}045$ sq. inch. Allowing 6 conductors per slot and a space factor of 0·43, the sectional area of the slots in the armature core will be $\dfrac{0{\cdot}045 \times 6}{0{\cdot}43} = 0{\cdot}627$ sq. inch.

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From experiments made by Mr. Hobart on the inductance of various-sized slots it appears that a difference of nearly 300 per cent. is made by placing the conductors in a deep slot, wide enough to take one conductor only, as compared with the same number of conductors wound in a single layer on a smooth core. But for slots with a depth up to three times the width the inductance is not excessive, and this is exceeded in many cases.*

Making the depth of the slots in our case 2·5 times the width, and the width of slots and teeth alike on the outer edge, we get, depth of slots = 1·25 inches, and width of slots = 0·5 inch. There being 1760 armature conductors, and 6 conductors per slot, we get $\frac{1760}{6} = 293{\cdot}3$ slots, and as we cannot have 0·3 of a slot, we must modify either the number of conductors or the number per slot. The nearest number which is a multiple of 8 and divisible by 6 is 1752. Taking this for the number of conductors, we get $\frac{1752}{6} = 292$ slots and 876 commutator segments, giving an average of slightly over 5 volts per segment, and 3 segments per slot. It is advisable to have not more than 3 segments per slot, for the coils connected to these bars will all be in the same strength of field at the same instant, while some of the bars will lag or lead relatively, especially if numerous.

The diameter of the commutator may now be calculated, for the circumference will be 876 × 0·28 inches, and the diameter

$$= \frac{\text{circumference}}{\pi} = \frac{876 \times 0{\cdot}28}{3{\cdot}1416} = 78 \text{ inches} = 6{\cdot}5 \text{ feet.}$$

Keeping to the dimensions, previously found, for the armature slots, we get the circumference of the armature $= 292 \times 2 \times 0{\cdot}5 = 292$ inches, for we have 292 slots and 292 teeth, each 0·5 inch wide. The diameter of the armature is therefore $= \frac{292}{3{\cdot}1416} = 92{\cdot}9$ inches, and with these figures we find the circumferential speed of the armature to be $\frac{292 \times 100}{12} = 2434$ feet per minute—a comparatively low speed.

Mr. E. K. Scott gives a rule for finding the diameter of the armature thus—

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* American practice differs greatly both in the size of the slots and the ratio of depth to width, which, except in the smallest sizes, is often 4 : 1 and over.

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$$\frac{\text{number of conductors} \times \text{current per conductor}}{\pi \times \text{diameter in inches}} = 500$$

and except for the very largest machines, the quotient should not exceed 700, in which case the design is skimped. If it falls below 300, it indicates too liberal dimensions. Applying this formula in our case, we have—

$$\frac{1752 \times 91}{3{\cdot}14 \times 92{\cdot}9} = 546$$

which comes very close to the mean of the values given above.

The diameter being settled, the axial length can be found from the formula—

$$\text{watts output} = KD^2LS$$

Taking Scott's value for $K = 0{\cdot}03$, we have—

$$400{,}000 = 0{\cdot}03 \times 92{\cdot}9^2 \times L \times 100$$

$$\text{therefore } L = \frac{400{,}000}{0{\cdot}03 \times 92{\cdot}9^2 \times 100} = 15{\cdot}5$$

We shall require 3 ventilating spaces, each about 0·5 inch wide, so that about 17 inches would seem to be a suitable value for the axial length.

We may now turn to the iron portion of the machine, and find the total flux per pole. The full electromotive force has to be developed by $\frac{1}{8}$ of the total armature conductors, *i.e.* by 219 conductors. The whole of these cut through the field of one pole in $\frac{1}{800}$ minute.

We have seen that the electromotive force developed in a bipolar machine is equal to $\frac{NCS}{10^8}$, and the same formula holds for a multipolar machine with ordinary lap winding. With other forms of winding the formula has to be modified slightly, owing to the number of parallel paths in the armature being different to the number of pairs of poles.

If p be the number of *pairs* of poles, then in one revolution, the total number of lines of force cut by the whole of the armature conductors is $= 2pN$ (N being the lines entering the armature from any one pole), and if C represents the *total* number of conductors, divided into any number of circuits in parallel, say p_1

[redacted]

circuits, then the total number of conductors in series available for building up the electromotive force $= \frac{C}{p_1}$, and at S revolutions per second we have—

$$\text{E.M.F.} = \frac{2pN \times \frac{C}{p_1} \times S}{10^8}$$

But in our case, with ordinary lap winding we have 4 pairs of poles and 8 parallel circuits, therefore $2p$ and p_1 cancel out, giving us the formula—

$$\text{E.M.F.} = \frac{N \times C \times S}{10^8}$$

Transposing the equation, we get—

$$N = \frac{\text{E.M.F} \times 10^8}{C \times S}$$

N being the total lines entering the armature from any one pole, and C the total number of armature conductors. In our case, therefore—

$$N = \frac{550 \times 10^8}{1752 \times 1{\cdot}66} = 18{,}836{,}000$$

As with two-pole machines, the magnetic leakage factor depends, to a certain extent, on the size of the machine, 15 per cent. being an average allowance for a machine of 400 kw. The values of magnetic leakage factor usually allowed are—

Capacity.	Leakage factor.
100 kw.	1·12 to 1·25
200 „	1·11 to 1·22
300 „	1·10 to 1·20
500 „	1·09 to 1·18
1000 „	1·08 to 1·16
2000 „	1·07 to 1·15

Taking the magnetic leakage factor as 15 per cent. in our case, we have—

N in field-magnet cores = 18,836,000 × 1·15 = 21,661,400 and therefore at a density of 15,000 lines per square centimetre we get—

$$\left.\begin{array}{l}\text{Sectional area of iron in the}\\ \quad\text{field-magnet cores}\end{array}\right\} = \frac{21661400}{15000}$$

$$= 1444 \text{ sq. cms. or } 224 \text{ sq. inches}$$

We have seen that the arc of the circumference of the field-magnet bore containing the pole pieces is, for a two-pole machine, somewhere about 240° or 250°; but in multipolar machines this rarely exceeds 235°, for with a large ratio of pole arc to pole pitch the neutral zone is very narrow, necessitating narrow brushes, and therefore a longer commutator. With this value each pole shoe contains an arc of the circumference of 29·36°.

The pole pitch, *i.e.* the angle between the centre of one pole and the centre of the next, is, in our case, 45°, and therefore the ratio of pole arc to pole pitch $= \frac{29·36}{45} = 0·65$ or 65 per cent. This value varies but slightly in all English, American, and Continental machines, being, as a rule, somewhere between the limits of 65 per cent. and 70 per cent.

When we have decided on the length of the air gap, the length of the curved surface of the pole shoes can be obtained from the ratio of pole arc to pole pitch.

The length of the air gap varies with the diameter of the armature. With a short air gap, armature reaction becomes excessive, and any slight deflection of the armature due to its weight causes great inequalities in the air-gap flux. The eddy currents induced in the pole face, with any given width of slots and teeth, varies rapidly when the length of the gap is shortened unduly, and for this reason the length of the air gap should not be less than half the width of the slots. On the other hand, if it be abnormally long, the excitation ampere turns become excessive. For the size we are considering it is not advisable to make the air gap less than $\frac{1}{3}$ inch. The usual values for the length of the air gap in modern multipolar machines are approximately as follows :—

[redacted]

Diameter of armature in inches.	Length of air gap in inches.
30	0·22
40	0·25
50	0·28
75	0·31
100	0·34
125	0·37
150	0·43
200	0·5

If we take the length of the air gap in our case as 0·33 inch, we get the diameter of the field-magnet bore equal to the diameter of the armature + twice the length of the air gap, or—

diameter of field-magnet bore = 92·9 + 0·66 = 93·56 inches

The circumference of the field-magnet bore is therefore $93·56 \times \pi = 293·8$ inches.

Mr. Mavor gives a simple rule for estimating the sparkless properties of a machine which we may apply at this point to see if our design is proceeding on satisfactory lines. For sparkless commutation, he states that the ampere turns per pole on the armature should not exceed, at full load, 10,000 per centimetre length of the air gap. In our case the air gap is 0·33 inch = 0·84 cm. in length, and therefore the full load ampere turns per pole must not exceed $\frac{10,000}{0·84} = 11,900$. With 1752 armature conductors, we have conductors per pole $= \frac{1752}{8} = 219$, and two conductors go to each turn. Therefore turns per pole $= \frac{219}{2}$ = 110, say. The ampere turns per pole are therefore $= 110 \times 91$ = 10,010, which is well within Mr. Mavor's figure.

Better commutation is obtained if the pole shoes are long and thin, so as to get highly saturated at the tips. This not only puts a high reluctance in the armature cross field, thus minimizing distortion, but the rise of electromotive force from the neutral point to the maximum is a more gradual growth.

The sectional area of the cores has been found to be 224 sq. inches, which, if made circular in section, gives a diameter of practically 17 inches, while if we elect to make them of square section, we get the length of each side = 15 inches. The radial length of the cores has to be great enough to hold the field winding without too great a depth, as explained in connection with

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two-pole machines on p. 151. With multipolar machines, in most cases a winding length about equal to the axial length of the iron in the core is usually sufficient to allow as a first approximation. There is a slight advantage in making the cores rather long, in that the cooling surface of the winding is increased, and therefore for a given temperature rise, a higher current density can be employed; but, on the other hand, the weight and over-all dimensions are increased, which usually outweigh the advantages gained. In our case, then, we may take—

Radial length of field magnet cores = 15 inches

The length of the curved surface of the bore included within the pitch is $= \frac{293·8}{8} = 36·7$ inches, and therefore the length of the surface of the pole shoes is $= 36·7 \times 0·65 = 23·8$ inches.

The radial depth of the shoes, whether of cast iron or laminated sheet steel, need not be great, providing they are deep enough to allow of proper mechanical support. A radial depth at the centre of 1 inch will probably be ample. The shape of these pole shoes is rather important, the main consideration being to shape them so as to minimize armature reaction, as explained on p. 197.

To effect this, the pole horn, which becomes *strengthened* by armature reaction, is sometimes cut away more or less. If the tips be long and thin, however, they usually become so highly saturated, especially if made of cast iron, as to give all that is desired in this respect.

We are now in a position to consider the dimensions of the field magnet yoke ring. The internal diameter must be equal to that of the field-magnet bore, plus twice the length of the field-magnet limbs and pole shoes. Therefore the internal diameter of the yoke ring is $= 93·5 + 32 = 125·5$ inches.

The yoke ring may be cast either in mild steel or iron, and with the former metal the sectional area should approximate to that of the field cores, while with the latter, the sectional area should be from 1·3 to 1·5 times greater, though the total lines carried by the yoke is only half the total generated in the field cores. One reason why the sectional area of the yoke ring should be fairly large lies in the fact that, owing to its large diameter and great weight, it has a tendency to fall slightly out of truth

[redacted]

when placed on its supports, and so alter the uniformity of the air-gap length. This may be largely overcome by so shaping it as to give a maximum stiffness for any given weight of metal. But it is advisable not to restrict the metal in the yoke, for if the magnetic density be run at all high, there will be an abnormal amount of magnetic leakage.

It was the practice in early multipolar machines to make the yoke polygonal in shape, but the yokes of modern machines are almost exclusively circular, with the edges well rounded in the section. The breadth is often made considerably greater than the depth so as to give better protection to the field coils, but the shape, with any given sectional area, is a point decided principally by the fancy of the designer. If we take an approximately rectangular section with a width roughly three times the depth and the corners well rounded off, we get—

Breadth of yoke ring = 24 inches
Radial depth of yoke ring = 8 inches
Over-all diameter of yoke ring = 149 inches

The lines of force in the armature core below the slots do not distribute themselves uniformly through the iron, but pass largely in the outer layers from pole to pole, the depth of iron penetrated by lines to any practical extent depending in part on the pole pitch, on the length of air gap, and on the magnetic density in the gap.

In some experiments conducted by Dr. Thornton, it was found that with pole pitch = 51° and $\frac{\text{pole face}}{\text{pole pitch}} = 0{\cdot}72$, 80 per cent. of the total lines entering the armature pass through the section between the armature face and a point in the core at a depth equal to twice that of a line joining the pitch lines at the armature face; the proportion being slightly greater with a long air gap. With pole pitch = 81°, 70 per cent. of the total lines passed through a similar section. The point of greatest density is, in each case, not far from the chord joining the centre line of the poles at the bottom of the slots. There would therefore seem to be no advantage, magnetically, in making the radial depth of the armature core very great.

We are now in a position to calculate the excitation required to produce the necessary armature flux. There will be four magnetic circuits in parallel, one to each pair of poles; but as these are all alike, we need only consider one (Fig. 146). A mean line is here shown dotted, the length of which is, approximately—

Field magnet limbs	= 30	ins. =	76	cms.
„ „ yoke	= 52	„ =	132	„
Armature core	= 36	„ =	91	„
Air gaps	= 0·66	„ =	1·676	„
Armature teeth	= 2·5	„ =	6·35	„

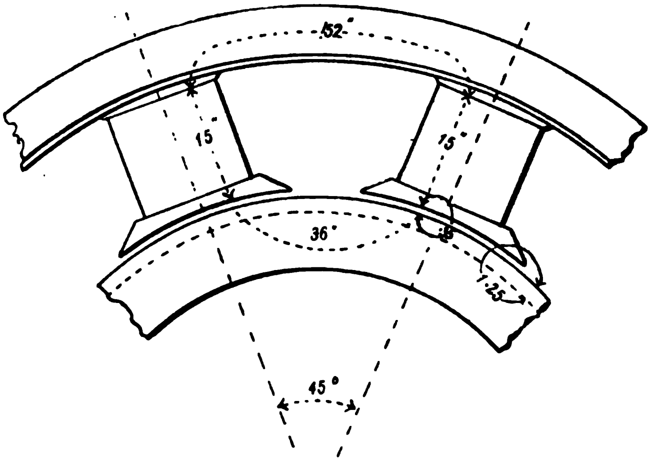

FIG. 146.

By comparing the values of magnetic density employed in various machines of modern manufacture, we find these of the order—

Field magnet limbs .	13,000 to 16,000	per sq. cm.
Air gaps . . .	7,000 to 9,000	„
Armature teeth . .	17,000 to 21,000	„
Armature core . .	9,000 to 12,000	„
Yoke ring (steel) . .	9,000 to 12,000	„
„ (iron) . .	4,500 to 6,000	„

The density in the field-magnet limbs we have already decided on, viz. 15,000, while the total lines in the air gap must necessarily be the same as in the armature, which, we have seen, must be = 18,836,000.

[redacted]

The sectional area of the curved surface of the pole shoes will be $23{\cdot}8 \times 17$ sq. inches. By adding $0{\cdot}8$ times the length of the air gap all round to allow for the fringing of the lines (see p. 31), we get—

$$\text{Sectional area of the air-gap} = [(23{\cdot}8 \times 2{\cdot}54) + 1{\cdot}35] \times [(17 \times 2{\cdot}54) + 1{\cdot}35]$$
$$= 2736{\cdot}5 \text{ sq. cms.}$$

$$\left.\begin{array}{r}\text{The density of the air gap flux}\\ \text{is therefore}\end{array}\right\} = \frac{18836000}{2736} = 6884$$

The lines of force in the air gap will embrace a certain number of armature teeth, and we must find this number before we can calculate the tooth density. The density in the teeth is usually fairly high, and in certain respects this is an advantage, for if the teeth be highly saturated, the higher will be the reluctance of the armature cross-magnetism circuit. But to saturate the teeth to any very great extent necessitates such an increase in the number of field ampere turns as to become impracticable. Even at 15,000 or 16,000 lines per sq. cm. the permeability of the teeth is so low that a fairly large number of lines cross in the space between the teeth. It therefore becomes necessary to apply a correction in estimating the correct tooth density. The curve (Fig. 147) shows the relation between the apparent tooth density, *i.e.* the density obtained by dividing the total armature flux by the sectional area of the teeth, and the corrected tooth density, allowing for leakage across the slots. The top, middle, and bottom curves refer to cases where the ratio $\frac{\text{width of tooth}}{\text{width of slot}} = 1$, $0{\cdot}75$, and $0{\cdot}5$ respectively.

The circumference of the armature we have found to be 292 inches, and the length of the curved surface of the pole shoes 23·8 inches. In the whole circumference there are 292 teeth, and therefore in $\frac{23{\cdot}8}{292}$ of the circumference there are 24 teeth, each tooth having a sectional area of iron at the surface, after deducting space occupied by ventilating ducts, and insulation between plates, of $13{\cdot}17 \times 0{\cdot}5 = 6.58$ sq. inches $= 42{\cdot}4$ sq. cms. But the slots are cut with parallel sides, and therefore the teeth will be smaller at the root. The width of a tooth at the root will be $= 0{\cdot}46$ inch $= 1{\cdot}16$ cm., and therefore the sectional area at the

[redacted]

base of the teeth will be 13·17 × 0·46 = 6·06 sq. inches = 39 sq. cms.

Taking a mean, we get, sectional area of each tooth = 41 sq. cms., say; the sectional area of iron in the teeth per pole will therefore be = 41 × 24 = 984 sq. cms.

The apparent magnetic density in the teeth will be $= \frac{18836000}{984}$ = 19,100 lines per sq. centimetre, and the corrected tooth density = 18700.

The average density of the lines in the armature core should be kept rather low, say 10,000 lines per sq. centimetre. The flux dividing in the core, as in the yoke, usually allows of this being obtained without an abnormal amount of iron. Taking this density in our case, we get, sectional area of iron in armature core below the slots $= \frac{9418000}{10000}$ = 942 sq. cms. = 146 sq. inches. Allowing for the ventilating ducts, and say 15 per cent. for insulation, as with the teeth, we get the length of iron along the shaft in the armature core = 14·2 inches, and therefore the depth of iron in the core below the slots $= \frac{146}{14·2}$ = 10 inches.

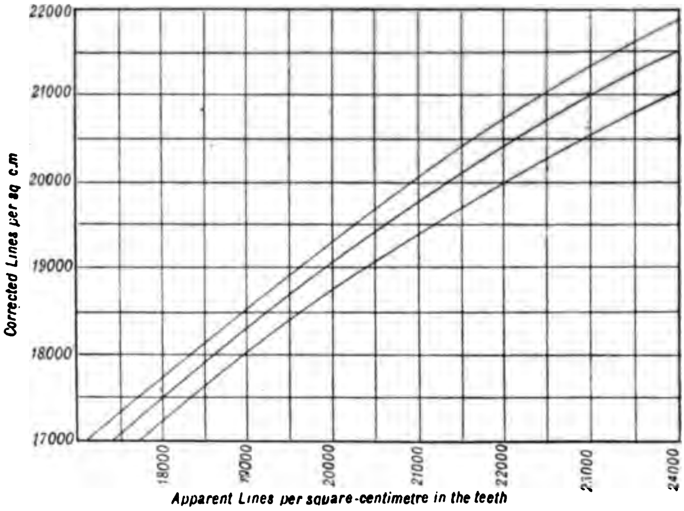

FIG. 147.

We have allowed the same sectional area in the cast-steel yoke

[redacted]

ring as in the field cores, but the flux in the former is only half that in the latter, owing to its dividing at this part. The density in the yoke ring will therefore be = 7500 lines per square centimetre.

Assembling these various lengths, sectional areas, and densities, we get—

Length of mean line in yoke . . = 52 inches = 132 cms.
„ „ „ armature core . = 36 „ = 91·4 „
„ „ „ air gaps . . = 0·66 „ = 1·67 „
„ „ „ teeth . . = 2·5 „ = 6·35 „
„ „ „ field-magnet limbs = 30 „ = 76·2 „
Sectional area of yoke . . . = 1444 sq. cms.
„ „ armature core . . = 942 „
„ „ air gaps . . . = 2736 „
„ „ teeth . . . = 984 „
„ „ field-magnet limbs . = 1444 „
Magnetic flux in the yoke . . = 10,830,700 lines.
„ „ armature core . = 9,418,000 „
„ „ air gaps . . = 18,836,000 „
„ „ teeth . . . = 18,836,000 „
„ „ field-magnet limbs = 21,661,400 „
Magnitic density in the yoke . . = 7500 lines per sq. cm.
„ „ „ armature core . = 10,000 „ „
„ „ „ air gaps . . = 6884 „ „
„ „ „ teeth . . = 18,700 „ „
„ „ „ field-magnet limbs = 15,000 „ „

By referring to the curves of magnetization of iron and steel on p. 25, we get—

Ampere turns per centimetre for the field-magnet limbs at a density of 15,000. . . . . . = 25.
Ampere turns per centimetre for the yoke at a density of 7500 . . . . = 5.
Ampere turns per centimetre for the air gaps at a density of 6884 . . . . = 5507.
Ampere turns per centimetre for the teeth at a corrected density of 18,700 . . . . = 180.
Ampere turns per centimetre for the armature core at a density of 10,000 . . . . = 8.

[redacted]

From the above, we get—

Total ampere turns required for the field-magnet limbs . . . . = $25 \times 76{\cdot}2 = 1905$.
Total ampere turns required for the yoke . . . . = $5 \times 132 = 660$.
Total ampere turns required for the air gaps . . . . = $5507 \times 1{\cdot}67 = 9197$.
Total ampere turns required for the teeth . . . . = $180 \times 6{\cdot}35 = 1143$.
Total ampere turns required for the armature core . . . . . = $8 \times 91{\cdot}4 = 731$.

Therefore the total ampere turns per pair of poles required for the no-load electromotive force of the machine is = 13,618, or, say, 6800 ampere turns per pole.

The eight field coils will be connected in series, and the ends joined, through a rheostat, to the terminals of the machine, or to the bus bars of an exciter set. The rheostat is inserted in the circuit to regulate the field excitation, and at no load the whole, or nearly the whole, of it should be in the circuit.

It will be seen that the end connections necessarily form a large proportion of the total length of each armature turn. The distance between the poles, measured on the armature face, is = 20 inches, and owing to the conductors having to be bent to clear each other, they must project about 10 inches from the armature face on either side, and therefore the length of the end connections at each end, per turn, will be approximately $2 \times \sqrt{10^2 + 10^2}$ = 28 inches, or—

Length of conductor per turn outside the slots = 56 inches.
Length of conductor per turn embedded in the slots = 34 „
Total length of one complete turn = 90 „

$$\text{The resistance of each turn cold} = \frac{\text{length}}{\text{sect. area}} \times \text{specific resistance}$$

$$= \frac{90}{0{\cdot}045} \times \frac{0{\cdot}66}{10^6} = 0{\cdot}00132 \text{ ohm}$$

Between any pair of brushes there are 219 conductors in series, and as one turn forms two conductors, we have—

[redacted]

Total number of turns in series . . . = 110, say.
Total resistance of armature turns between any
two brushes . . . . = $0·00132 \times 110$
= 0·1452 ohm.

The brushes connect the winding into eight such circuits in parallel, and therefore the resistance of the complete armature is equal to $\frac{0·1452}{8} = 0·018$ ohm.

Allowing for the increase in resistance of the conductors at full load, due to their temperature coefficient, for a rise of 50° C. we have, resistance of whole armature = 0·023 ohm. The full load CR, drop in the armature will therefore be, approximately, $= 0·023 \times 728 = 16·7$ volts, and C^2R loss in the armature at full load $= 728^2 \times 0·023 = 12{,}190$.

In bipolar machines the lead of the brushes from the mid-pole position at full load is usually such as to bring the brush contact into the line drawn from the leading pole tip to the centre (p. 116). That is to say, the angular advance of the brushes is 50 per cent. of the angle between the pole tips. The conductors, therefore, included in *twice* this angle, are carrying currents in such a direction as to produce a *back* magnetizing force. With drum winding, we require two armature conductors to form one turn, and therefore the total number of armature *turns*, acting as demagnetizing turns, is equal to the number of conductors so acting divided by two.

In multipolar machines a smaller brush lead will usually suffice. This rarely exceeds 35 per cent., and in many cases not more than 30 per cent., of the angular space between adjacent pole tips.

Taking a mean value of 32 per cent. in our case, the number of conductors producing a back magnetizing force will be the number included in 64 per cent. of the interpolar space. This number is easily obtained from the total number of armature conductors and the ratio of pole arc to pole pitch. The total number of conductors is 1752, and the ratio of pole arc to pole pitch is 65 per cent. Therefore 65 per cent. of 1752 will be the number of conductors embraced by the whole of the polar faces, the remaining 35 per cent. being in the interpolar spaces.

Therefore we have—

Total conductors in each interpolar space $= \frac{1752 \times 0{\cdot}35}{8} = 76$

Total conductors acting as back magnetizing conductors $= 76 \times 0{\cdot}64 = 49$

Total *turns* per pole acting as back magnetizing turns $= \frac{49}{2}$ = (say) 25

Full-load current per conductor = 91 amperes.

Therefore back ampere turns at full load per pole $= 91 \times 25 = 2275$, or 4550 per magnetic circuit

In addition to the armature CR drop we have a further drop, due to brush-contact resistance, brush leads and gear, which, in most large multipolar machines, is found to be about 1 per cent. of the terminal voltage. This, in our case, is 1 per cent. of 550 = 5·5 volts.

The total volts drop at full load, due to armature and brush resistance, is therefore = 22·2 volts.

The number of additional ampere turns at full load required to develop an electromotive force equal to the CR drop will be obtained in a similar way to that used in calculating the no-load excitation. Therefore—

$$22{\cdot}2 = \frac{N \times 1752 \times 100}{10^8 \times 60}$$

therefore
$$N = \frac{22{\cdot}2 \times 10^8 \times 60}{1752 \times 100} = 760{,}200$$

And the density of each part must be increased by these additional lines at full load, allowing also for leakage factor with the additional flux.

The full-load flux through the various parts will therefore be as follows:—

Full-load flux in the yoke . . . . = 11,167,815.
,, ,, ,, armature core . = 9,798,100.
,, ,, ,, air gaps. . . = 19,596,200.
,, ,, ,, teeth . . . = 19,596,200.
,, ,, ,, field-magnet limbs. = 22,535,630.
Full-load density in the yoke. . . = 7,664.
,, ,, ,, armature core . = 10,400.
,, ,, ,, air gaps . . = 7,052.
Full-load density in the teeth (corrected for leakage in the slots) . . . = 19,300.
Full-load density in the field-magnet limbs = 15,600.

Owing to the low density and consequent high permeability in the yoke and armature core, they will add but very little reluctance at the altered density, and no great error would be made in neglecting these parts. Referring again to our magnetization curves, we find, to change the density from that at no load to the values above for full load, we require—

			Ampere turns per cm.
For the armature core	from	10,000 to 10,400	= 1.
„ air gaps	„	6,779 to 7,052	= 218.
For the teeth (corrected for leakage in slots)	„	18,700 to 19,300	= 60.
For the field magnet limbs	„	15,000 to 15,600	= 10.

Total additional ampere turns required—

For the armature core . .	= 91 × 1	= 91.
„ air gaps . . .	= 218 × 1·67	= 364.
„ teeth . . .	= 60 × 6·35	= 381.
„ field-magnet limbs .	= 10 × 76·2	= 762.

giving a total of 1598 additional ampere turns at full load, to which must be added the number of back ampere turns, viz. 4550, making in all 6148 additional ampere turns to be provided per pair of poles, or a grand total of 9880 amp. turns per pole.

The full-load potential difference of the machine (= 550 volts) will be divided up among the eight coils in series, so that volts per coil = 68, say. The current, multiplied by the resistance of each coil, must therefore be = 68, or—

$$\text{Volts} = \text{current} \times \text{resistance} = \text{C} \times \frac{l}{\text{sec. area}} \times \text{specific resistance}$$

$$= \frac{\text{ampere inches}}{\text{sec. area in sq. inches}} \times \text{specific resistance per cubic inch hot.}$$

Therefore—

$$\text{sec. area} = \frac{\text{amp. inches} \times \text{sp. resistance}}{\text{volts per coil}}$$

The length of a turn at the bottom of the spool, close to the field core, will be 60 inches, plus about 2 inches for insulation, and allowing a depth of 2·75 inches, the length of a turn at the surface will be 82 inches, therefore mean length of one turn = 72 inches. We therefore get—

$$\text{sec. area} = \frac{72 \times 9880 \times 0{\cdot}75}{68 \times 10^6} = 0{\cdot}0078 \text{ sq. inch.}$$

This is a size between Nos. 12 and 13 S.W.G. The nearest size would be No. 13 B.W.G., which has a sectional area of 0·0070, and a diameter covered of 0·115 inch.

If we are proposing to compound the machine, we must reserve about one-third of the winding length for series turns, in which case we get the winding length for shunt turns = 10 inches. The diameter of the covered wire being 0·115 inch, therefore in 10 inches we can get 86 turns; and in 2·75 inches depth we can get 23 layers, giving a total of 1978 turns per pole.

We want a total of 9880 amp. turns per pole, and therefore the exciting current at full load must be $\frac{9880}{1978}$ = 5 amps. practically.

At no load we want only 6800 amp. turns per pole, and therefore the exciting current at no load will be $\frac{6800}{1978}$ = 3·4 amps., which will be obtained by putting in the field rheostat.

The resistance of the whole of the shunt winding hot will be $= \frac{550}{5} = 110$ ohms, and the resistance of shunt winding and field rheostat combined $= \frac{550}{3{\cdot}4} = 161$ ohms. Therefore the resistance of the field rheostat alone must be = 51 ohms approximately when at its final temperature. The rheostat is usually divided up into a large number of sections connected to a multiple-contact switch.

The total watts lost in the shunt winding = 5 × 550 = 2750 = $\frac{1}{145}$ of the machine output. Therefore watts absorbed per coil = $\frac{2750}{8}$ = 344. Surface area of coil = 820 sq. inches, therefore watts per square inch of surface = $\frac{344}{820}$ = 0·41.

If the machine is to be used for traction, where the variations in load are very severe and very sudden, it is usual to over-compound the machine by about 10 per cent., to allow for drop on the feeders. In this case the terminal pressure rises from 550 to 605 volts at full load, that is, an additional 55 volts have to be generated, in addition to the 22·2 volts for armature and commutator *CR drop.* *To find* the additional ampere turns required for this, and therefore the number of series turns to be provided, we proceed as before. We then get—

$$77{\cdot}2 = \frac{N \times 1752 \times 100}{10^8 \times 60}$$

therefore $$N = \frac{77{\cdot}2 \times 10^8 \times 60}{1752 \times 100} = 2,644,400$$

= additional flux at full load to be provided per pair of poles

Therefore—

Full-load flux in the armature core . . = 10,740,200.
" " " air gaps . . . . = 21,480,400.
" " " teeth . . . . . = 21,480,400.
" " " field-magnet limbs. . = 24,702,460.
Density in the armature core at full load . = 11,400.
" " air gaps at full load. . . = 7,730.
Apparent density in the teeth at full load . = 21,830.
Corrected density in the teeth at full load . = 20,500.
Density in the field-magnet limbs at full load. = 17,170.

Additional ampere turns per centimetre to change density—

For the armature core . from 10,000 to 11,400 = 5.
" air gaps . . " 6,779 to 7,730 = 761.
" teeth . . " 18,700 to 20,500 = 200.
" field-magnet limbs " 15,000 to 17,170 = 55.

Total additional ampere turns required—

For the armature core . . . = 5 × 91 = 455.
" air gaps . . . . . = 761 × 1·67 = 1270.
" teeth . . . . . = 200 × 6·35 = 1270.
" field-magnet limbs . . = 55 × 76·2 = 4190.
Total . . . . . . = 7185.

Adding to this the 4550 back ampere turns at full load, we get—

Additional ampere turns to be provided at full load for 10 per cent. over-compounding . . . . = 11,735.

The full-load current is 728 amperes, and therefore we require $\frac{11735}{728} = 16$ turns per pair of poles of series winding, or series turns per pole = 8.

The current density in the series winding is usually between 800 and 1000 amps. per square inch at full load.

Taking a current density of, say, 900 amps. per square inch, the sectional area of the series winding will be $\frac{728}{900}$ = 0·8 sq. inch.

We have still to decide on the length of the commutator. The carbon brushes should not cover more than two, or at the most three, bars. If we allow three bars, we get for the curved surface of the brush contact $3 \times 0{\cdot}28 = 0{\cdot}84$ inch.

The current to be collected by each line of brushes will be 182 amps., and at a current density in the brush contact of 30 amps. per square inch we get the sectional area of brush contact $= \frac{182}{30} = 6$ sq. inches, say. The length of brush contact along the shaft will therefore be $= \frac{6}{0{\cdot}84} = 7{\cdot}14$ inches.

The brushes commonly employed are about one and a half inches wide, though any size can be obtained. With this width we shall require five brushes in each set. Each brush-holder will take up about a quarter of an inch in length, or 1·25 inches in all, and a little space must be allowed at each end, which will necessitate a clear commutator surface of 9 inches, exclusive of lugs and clamps. The lugs should be about one inch in width, and the depth of the segments—to allow of, say, one inch wearing depth—about two inches. The commutator will therefore have the dimensions given in Fig. 148, while the mechanical construction will be decided from the considerations given in the preceding chapter.

We may now calculate the reactance voltage at full load by the method given on p. 113, in which case we get—

Total length of embedded portion of armature winding per turn = 86 cms.
Total length of free portion per turn = 152 cms.
Total number of turns short-circuited by a brush = 3
Peripheral speed of the commutator = 400 inches per second
Width of the curved surface of each brush = 0·7 inch
Current to be commuted = 91 amps.

$$\text{Frequency of commutation} = \frac{400}{2 \times 0{\cdot}7} = 333$$

$$L = \frac{(86 \times 3 \times 4) + (152 \times 3 \times 0{\cdot}8)}{10^8} = 0{\cdot}000014$$

$$\text{Reactance voltage} = 2\pi n \text{LI} = 6{\cdot}28 \times 333 \times 0{\cdot}000014 \times 91$$
$$= 2{\cdot}6 \text{ volts}$$

The various losses can be calculated approximately, and the efficiency at different loads so determined. The losses include (1) watts lost in commutator and brush contacts, (2) watts lost in the armature winding, (3) watts lost in the armature core, (4) watts lost in the shunt winding and rheostat, (5) watts lost in bearings and air friction.

The commutator losses are of two kinds, contact resistance (C^2R) loss, and friction loss, which may be calculated approximately thus: The contact resistance loss depends on the current density and the pressure between the brushes and the commutator, and is usually close to thirty watts per square inch, with a current density of 30 amps. per square inch and a pressure of about 1·5 pounds per square inch. As we have a total area of brush contact equal to 52 sq. inches, this will give, in our case, 30 × 52 = 1560 watts, which is very near to the total current multiplied by two, a value given by Mr. Friedlaender for the ohmic loss. The friction loss also depends on the pressure between the brushes and commutator, on the circumferential speed of the commutator in feet per minute, and on the coefficient of friction between carbon and

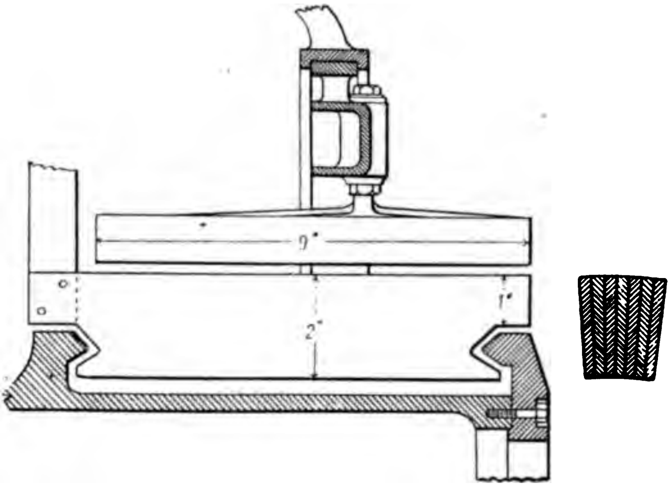

FIG. 148.

copper, which has been found by experience to be close to 0·3 for most kinds of carbon used.

The commutator friction loss in foot-pounds per minute is therefore—

$$= 1\cdot5 \times 52 \times 2042 \times 0\cdot3 = 47782 \text{ foot-pound per minute}$$
$$= 796 \text{ ,, ,, ,, second}$$

One watt being equal to 0·7373 foot-pounds per second, we get, friction loss in watts $= \frac{796}{0\cdot7373} = 1080$.

Total commutator loss = 2640 watts.

The armature core losses might be calculated by considering the hysteresis and eddy current losses separately and applying the formulæ given on p. 62. The latter is, however, not easy to calculate accurately, and the actual value found by experience, on test, is usually considerably greater than the calculated value. This is probably due to a variety of causes, such as eddy currents in the pole faces, unequal distribution of flux in the core, burring due to filing or machining the slots, etc. The usual practice is to take values found by experience for various flux densities, such as those given in Fig. 149, and calculate the volume and density in the teeth and core separately, and read off the loss per cubic centimetre per cycle direct. In our case we have—

Mean sectional area of iron in the teeth per pole = 984 sq. cms.
Total mean sectional area of teeth = 7872 sq. cms.
Length of teeth = 1·25 inches = 3·17 cms.
Total volume of teeth = 24,954 cubic cms.
Density in the teeth at full load = 20,500.
Watts per cubic centimetre per cycle (from curve) = 0·0065.

$$\text{Cycles per second} = \frac{\text{revs. per minute} \times \text{pairs of poles}}{60} = 7.$$

Total watts lost per cycle in teeth = 24,954 × 0·0066 = 164.
Total loss in the teeth = 164 × 7 = 1148.
Cross sectional area of iron in core below teeth = 942 sq. cms.
Mean total length of core = 251 inches = 648 cms.
Volume of iron in core = 942 × 648 = 610,416 cubic cms.
Mean density in the core = 11,400.

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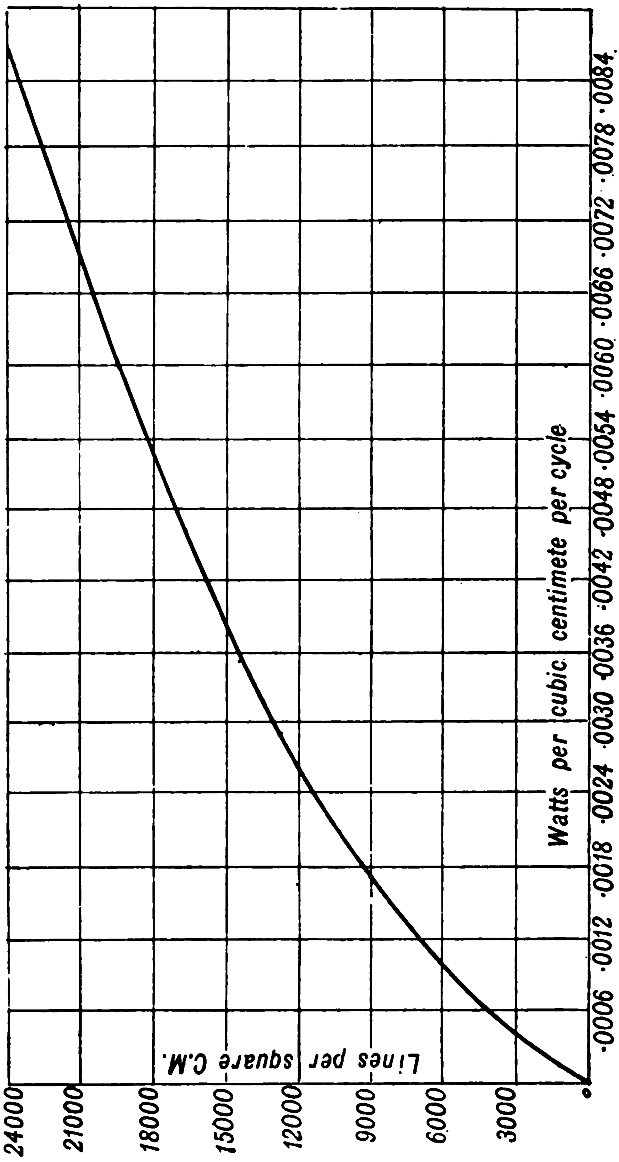

FIG. 149.

Watts per cubic centimetre per cycle (from curve) = 0·0024.
Total watts per cycle = 1465.
Total watts lost in core below teeth = 1465 × 7 = 10,255.
Approximate total loss in core and teeth = 11,400 watts.

The C^2R loss in the armature winding at full load we have found to be 12,190 watts, and that in the shunt winding 2750 watts. At no load the loss on the shunt winding and rheostat combined is 1870 watts.

The loss due to bearings and air friction has been found by experiment to be approximately equal to $0·0003D^2LR$ watts, where D = diameter of armature in inches, L the length of the armature in inches, R the speed in revolutions per minute. Inserting these values, we have—

Watts lost in air and bearing friction = 0·0003 × 8519 × 17 × 100
= 4344 watts.

Assembling these, we have at full load—

Commutator loss	=	2,640	watts
Armature C^2R loss . . .	=	12,190	„
Shunt winding loss . . .	=	2,750	„
Armature core loss . . .	=	11,400	„
Bearing and air friction loss . . .	=	4,344	„
Approximate total losses at full load	=	33,324	„
or approximately		33,300	„

In multipolar machines of large size, with well-ventilated slotted armature, there is usually about 15° C. temperature rise for every watt per square inch of peripheral surface, taken over the whole of the winding. In our case the total armature loss is 23,590 watts, and the peripheral surface of the winding = 10,800 sq. inches, therefore the watts per square inch = 2·18, and the probable temperature rise at full load = 2·18 × 15 = 32° C.

For each watt per square inch of commutator surface there is usually a temperature rise of about 14° or 15° C., and in our case the watts per square inch are practically equal to 1·2, and therefore the probable temperature rise in the commutator will be about 18° C.

The core loss will be *nearly* constant at all loads, being rather less at small loads owing to the slightly lower magnetic density employed. The air and bearing friction and the commutator friction losses are also independent of the load. The variable losses are the armature, commutator, and, to a small extent, shunt excitation C^2R losses.

The approximate efficiency at full load will be $\frac{400000}{433300}$ . . . . . = 0·92, or 92 per cent.
The approximate efficiency at $\frac{3}{4}$ load will be $\frac{300000}{329860}$ . . . . . . = 0·91, or 91 „ „
The approximate efficiency at $\frac{1}{2}$ load will be $\frac{200000}{226400}$ . . . . . . = 0·88, or 88 „ „
The approximate efficiency at $\frac{1}{4}$ load will be $\frac{100000}{123000}$ . . . . . . = 0·81, or 81 „ „

The following are particulars of some successful modern multipolar direct-current dynamos. The first, designed by Messrs. W. C. Mountain and J. Leggat, is a 12-pole 300-kw. 240-volt machine, running at 90 revolutions per minute. The machine is designed to stand an over-load of 25 per cent. for three hours, otherwise its output would be greater. On test, the temperature rise in the armature was found to be 48° F. or 26·6° C., in the field winding 53° F. or 29·5° C., and in the commutator 62° F. or 35° C.

Diameter of the armature	78 ins.
Number of armature conductors	1584
Length over conductors	27·5 ins.
Length over discs	13 „
Net length of iron	10·8 „
Depth of slots	2 „
Width of slots	0·45 „
Number of slots	264
Sectional area of conductors . . .	0·072 sq. in.
Space factor	0·48
Ventilating ducts	2
Width of each duct	0·5 in.
Conductors per slot	6
Mean length of conductor	38·9 ins.
Resistance between brushes . . .	0·0039 ohm.
Current density in conductors . . .	1447 amps. sq. in.
Armature ampere turns	13,750
Full-load armature flux	10,000,000 lines
Area of teeth under pole	77 sq. ins.
Length of air gap	0·375 in.
Area of air gap	189 sq. ins.
Magnetic length through armature . .	18·7 ins.
Sectional area of armature	154 sq. ins.
Diameter of commutator	60 ins.

Number of segments	792
Width of segments at surface	0·2072 in.
Thickness of mica insulation	0·03 "
Rubbing length of commutator	6 ins.
Sets of brushes	·12
Brushes per set	3
Contact area per brush	2 × 1 ins.
Angle of lead of brushes	3 degrees
Length of field pole arc	14·5 ins.
Ratio of pole arc to pole pitch	70 per cent.
Radial length of cores	12·25 ins.
Diameter of cores	12 "
Diameter of field bore	78·75 "
Over-all diameter	118 "
Leakage factor	1·15
Flux in field coils	11,500,000 lines
Sectional area of field cores	114 sq. ins.
Sectional area of yoke	280 "
Magnetic length through yoke	30 ins.
Total ampere turns per circuit	28,866
Ampere turns in shunt per circuit	20,333
Ampere turns in series per circuit	8533
Series turns per coil	3·5
Sectional area of series winding	1·35 sq. in.
Shunt turns per bobbin	660
Sectional area of shunt winding	0·0324 sq. in.

Fig. 150 gives a view of this machine.

The following particulars refer to a 16-pole machine designed by Mr. Hobart, given by him in a paper read before the Institution of Electrical Engineers. The machine is of 1000 kw. capacity at 500 volts, running at 90 revolutions per minute. It has a guaranteed over-load capacity of 25 per cent. for one half-hour. The temperature rise not to exceed 50° C. during continuous running at full load. No serious sparking or heating with momentary overload of 50 per cent. Fixed brushes for all loads.

External diameter of armature	350 cms.
Length of armature over winding	80 "
Length over armature core	35 "
Number of ventilating ducts	8
Width of each duct	1·3 cms.
Effective length of armature laminations	22·5 "
Internal diameter of armature laminations	28·1 "
Diameter of commutator	270 "
Length of commutator	38 "
Width of segment at surface	0·74 "
Thickness of mica insulation	0·076 "
Total number of segments	1152

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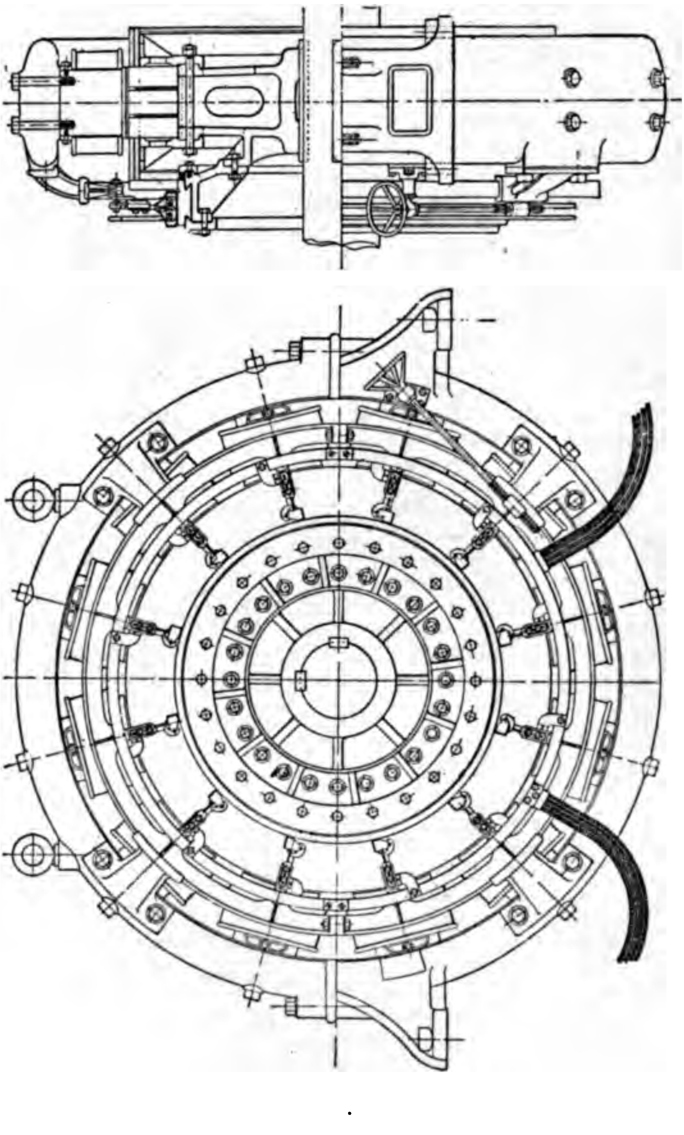

FIG. 150.

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Total number of slots	384
Segments per slot	3
Turns per segment	1
Width of slot	1·34 cms.
Depth of slots	3·2 „
Length of air gap	1 „
Length of field cores	48 „
Diameter of magnet core	38 „
Sectional area of magnet cores . . .	1140 sq. cms.
Pole face dimensions	35 × 49 cms.
Ratio of pole arc to pole pitch . . .	71 per cent.
External diameter of yoke	531 cms.
Width of magnet yoke	70 „
Thickness of magnet yoke	30 „
Armature conductor dimensions . . .	1·25 × 0·28 „
Current density in armature . . .	2300 amps. sq. in.
Thickness of slot insulation . . .	0·16 cm.
Space factor	0·49
Average voltage per segment . . .	7·7
Current density in brush contact . . .	32 amps. sq. in.
Reaction ampere turns per pole . . .	9000
Number of paths in armature winding . .	16
Amperes per path	125
Length of arc of brush contact	2 cms.
Frequency of commutation . . .	318
Mean length of armature turn . . .	240 cms.
Embedded length per turn	45 „
Reactance voltage at full load . . .	3·9
Apparent tooth density	22,700
Radial depth of laminations below slots .	31 cms.
Density below slots	10,700
Full-load armature flux	14,900,000 lines
Leakage factor	1·125
Flux in field cores	16,800,000 lines
Density in field cores	14,900
Density in yoke	4000
Pole face density	8700
Full-load ampere turns	14,000
No-load ampere turns	11,000
Armature reaction ampere turns . . .	3000
Material of magnet yoke	cast iron
Material of field cores	cast steel
Material of pole shoes	cast iron
Material of armature laminations . . .	sheet steel
Peripheral speed of armature . . .	3200 ft. per minute
Peripheral speed of commutator . . .	2480 „ „
Commercial efficiency at full load . .	94·1 per cent.
„ „ three-quarter load .	94 „
„ „ half load . .	92·9 „
„ „ quarter load . .	88·5 „

Fig. 151 represents a power station generator, made by Messrs. Crompton & Co., of 840 kw. 600 volts, designed to run at the relatively high speed of 230 revolutions per minute. It has 12 poles of laminated sheet iron cast-welded into the yoke ring; the armature being 90 inches in diameter, and 18 inches in length across the core discs. An overload capacity of 35 per cent. for

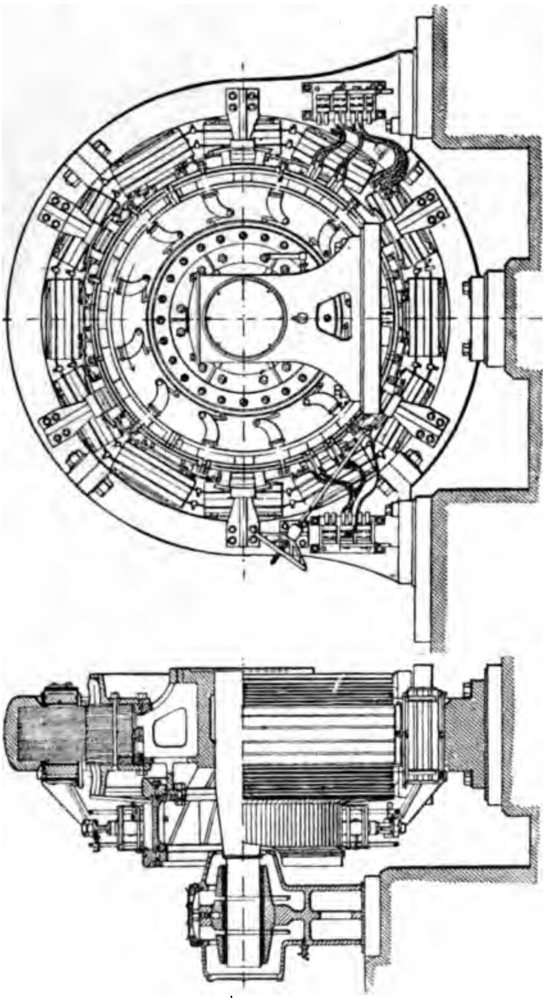

FIG. 151.

[redacted]

two hours, and a full-load commercial efficiency of 96·5 per cent., with a temperature rise of 70° F., is guaranteed. It has 250 slots, with six conductors per slot, and an air-gap length of 0·625 inch. The commutator is 58 inches in diameter, and therefore has a peripheral speed of 3492 feet per minute; the peripheral speed of the armature being 5419 feet per minute. There are 1500 armature conductors, and one turn per commutator segment. The magnetic density in the teeth and armature core is fairly low, on account of the large core loss produced at high speed with large densities. The maximum tooth density is 15,500 lines per square centimetre, and the density in the core below the slots 5000 lines per square centimetre. In the field cores the density is 16,500, and in the air gap 7000 lines per square centimetre. The series coils are wound outside the shunt, with a space between for ventilation.

CHAPTER XII

SINGLE-PHASE ALTERNATORS

We have seen that when a coil revolves in a two-pole or multipolar field, an alternating electromotive force is induced in it, which may be converted into a direct current for the outside circuit by the mechanical device of the commutator, though still retaining its alternating nature in the armature. In a great many cases there is an advantage in using, in the external circuit, the alternating current as generated. The intervention of the commutator, which, as we have seen, is mechanically the weakest part of the dynamo, can then be dispensed with. When this is done, however, it is found advantageous to modify the construction somewhat.

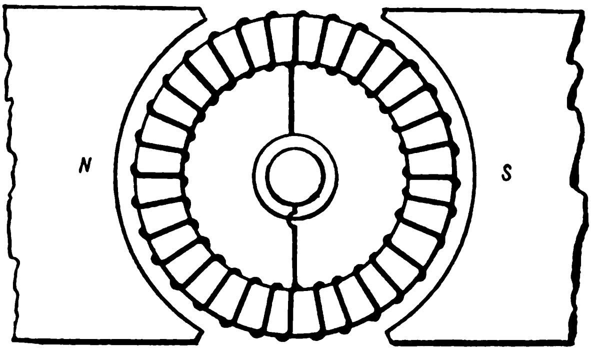

Fig. 152.

Take a two-pole field, for instance, with a gramme or ring winding, forming a closed circuit, with usually a series of tappings to the commutator lugs. If we remove the commutator, and leave only two diametrically opposite tappings, connected to insulated rings on the shaft, with a fixed insulated brush in contact with each, we shall have divided the winding into two equal

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coils in parallel, as shown in Fig. 152. Each half of the winding, therefore, develops the full electromotive force. In fact, we should get exactly the same electromotive force by using one half of the winding only, leaving half the iron core bare. The two halves being in parallel, however, we are able to take twice the current of one coil alone.

In the position shown in Fig. 152, each half of the winding is developing its maximum electromotive force at the brushes, while in Fig. 153 it has dropped to zero. In this latter position we have still electromotive forces induced in the winding, which are the same for all positions of the tappings, seeing that we have the same number of conductors cutting at the same rate through the same field, but in respect of the electromotive force at the brushes, the tappings connected to them are now in contact with two points of the winding, which are equal in potential, and we therefore get no potential *difference* between them. Each half of the winding, on either side of the tappings, which before gave rise to a maximum electromotive force at the brushes, is now cutting through the field in opposite directions to equal extent, and therefore develops two opposing electromotive forces. It will be seen that for all other positions of the tappings the electromotive force induced, in respect to the brushes, will have intermediate values. For instance, in Fig. 154 the electromotive force induced in that part of the winding facing the N pole will be greater than that in the remaining portion in the opposite direction, and the difference between the two will be the brush electromotive force, and as the

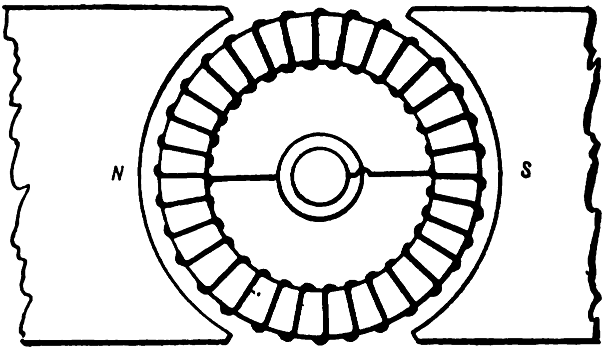

FIG. 153.

one part has been steadily increasing, while the other has been steadily decreasing, from the time the tappings were horizontal, and continue to do so until the tappings are vertical once more, the potential difference at the brushes has been steadily rising from the one position to the other.

It will be noticed that by this arrangement we get our alternating potential difference owing to the opposition of two electromotive forces for most of the cycle. It is clear, therefore, that the winding is not utilized to its greatest advantage. In Fig. 154, for instance, we should get a higher potential difference at the brushes in this position if the opposing parts were removed altogether, *i.e.* if the coils were narrower, for the electromotive force induced in these is lowering the value of the potential *difference* at the brushes.

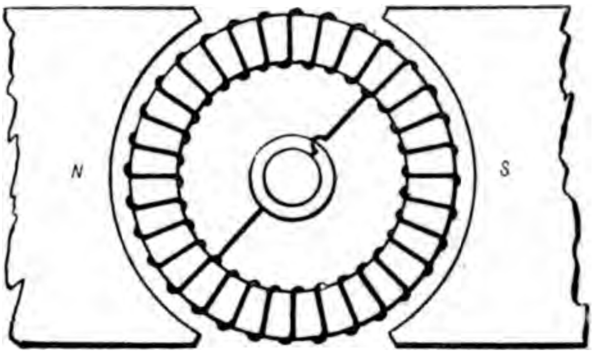

FIG. 154.

We might overcome this differential action very largely by winding two narrow coils, as shown in Fig. 155. There would then be practically no differential action, but the electromotive force would in this case be small, for we waste so much of the available armature space. The coils might now be put in series, instead of parallel, for they will always reverse at the same time, and add their electromotive forces together for the potential difference at the brushes (Fig. 156). Evidently we could wind on more turns in the coils if we narrowed down the pole arc; for instance, if we reduce the pole arc so as to embrace quarter of the armature circumference, then each coil may be enlarged so as to cover quarter of the armature face, and still be connected in series, with practically no differential action (Fig. 157).

The periodicity obtained by such a machine (see p. 53) will be equal to the speed in revolutions per second, for at each revolution either coil will have cut through the field twice, but in reverse directions, passing through maximum and minimum values twice, thus giving rise to a cycle of changes in potential difference at the brushes, as indicated in the curve (Fig. 19, p. 39).

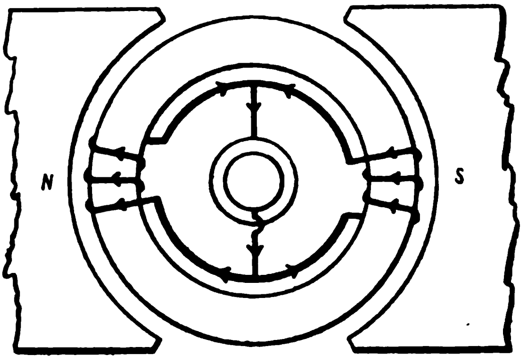

FIG. 155.

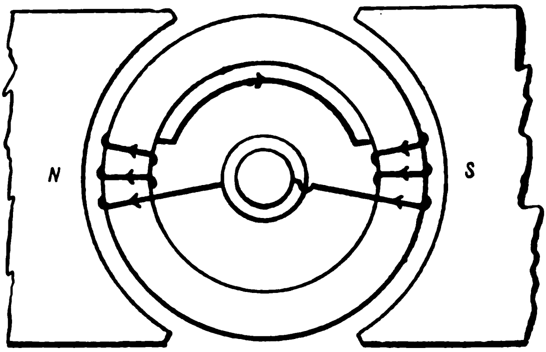

FIG. 156.

Unless the pole pieces are shaped somewhat, with the horns tapering off, and the air gap enlarging slightly at the tips, the *curve of* electromotive force induced would not be a sine curve, for with the pole pieces as shown in Fig. 157, the field passes radially across the gap over a fair length of the space, which gives rise to a more uniform rate of cutting over this part, and an electromotive force curve more flattened at the top, as shown in Fig. 26. In practice, it is seldom that pure sine waves of electromotive force are developed, though for purposes of calculation they are usually assumed to be so, without any large errors. To approximate more nearly to a sine wave—which is advantageous from every point of view—the pole shoes are very frequently more or less "shaped" on the face. This gives a varying length to the air gap, the reluctance increasing from the centre to the tips, which (if of the right proportions), produces a very fair approximation to a sine wave.

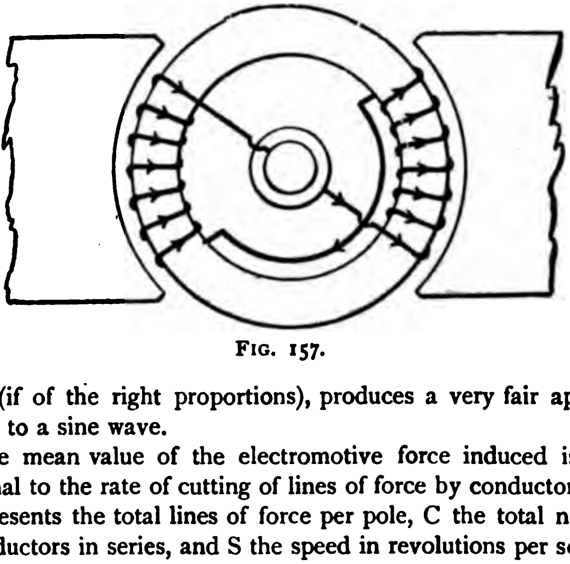

FIG. 157.

The mean value of the electromotive force induced is proportional to the rate of cutting of lines of force by conductors. If N represents the total lines of force per pole, C the total number of conductors in series, and S the speed in revolutions per second, then in one second the total lines of force cut will be 2NS, and being cut by C conductors, we get for the mean electromotive force $\frac{2NSC}{10^8}$ volts.

If we assume that the wave of electromotive force will have a sine variation, the form factor, *i.e.* the ratio of the effective to the mean value, will be = 1·11, or—

$$\frac{\text{effective volts}}{\text{mean volts}} = 1{\cdot}11 \text{ (see p. 50)}$$

therefore effective volts = mean volts × 1·11

[redacted]

The effective electromotive force induced is therefore—

$$= \frac{2\text{NSC}}{10^8} \times 1{\cdot}11 = \frac{2{\cdot}22\text{NSC}}{10^8}$$

This formula has to be modified in most cases, as we shall see presently.

The periodicity with such an arrangement as shown in Fig. 157 would be very low with the usual speeds employed. Even with turbine driving, running at a speed of, say, 2000 revolutions per minute, which is only possible with small sizes, we have a periodicity of $\frac{2000}{60} = 33$ only, so that some modification is required, for, except in traction work, the frequency ranges from 40 to 100 cycles per second. To obtain a higher frequency at any given speed, a larger number of poles may be employed, for the electromotive force will change through one complete cycle, as the coils cut through the field of each pair of poles. The frequency is therefore = number of pairs of poles × revolutions per second.

Most modern alternators have a large number of poles, the machines running at a relatively low speed, depending on the maximum permissible peripheral velocity which is usually somewhere between 5000 and 6000 feet per minute, except in turbine driving, where the peripheral speed often amounts to 16,000 or 17,000 feet per minute, necessitating quite a special construction. In some machines the armature rotates, while in others the field magnet is the revolving part. With the limiting peripheral speed just mentioned of 6000 feet per minute, we get—

Revolutions per minute.	Diameter in feet.
75	25·4
100	19·1
200	9·5
300	6·4
400	4·8
600	3·2
800	2·4
1000	1·92
1200	1·6
1800	1·06

Fig. 158 shows a type of revolving armature machine, while Fig. 159 shows a revolving field alternator.

These machines are of two distinct types: (1) those with a large number of turns, wound in deep slots in an iron core; (2) those with cores of some non-magnetic material. The first will be typical of machines having large inductance in their armature circuits, and a poor inherent regulation characteristic; while the second will have very little inductance and be better regulating machines, requiring but slight adjustment of excitation between no load and full load.

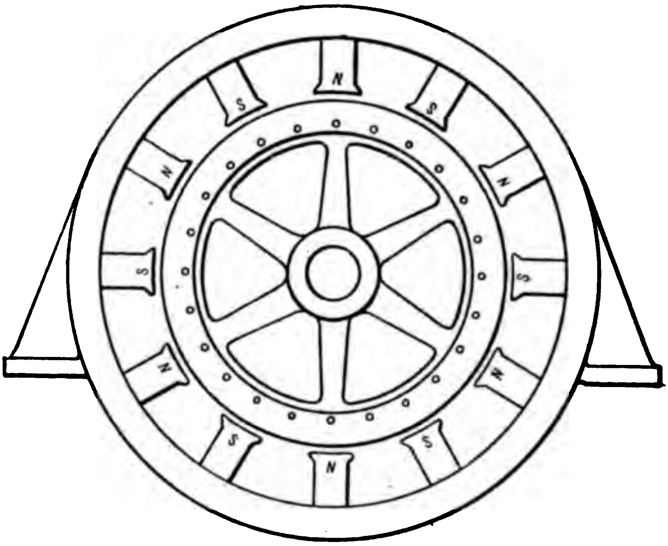

FIG. 158.

The inherent regulation may be stated as the percentage variation in the terminal potential difference between no load and full load, when the excitation is unchanged. Fig. 160 shows a typical inherent regulation curve for a machine of the first type, with full-load current of 80 amps. at 5000 volts, where from full load to no load the terminal potential difference rises from 5000 to 7500 volts, with constant excitation. To keep a constant potential difference of 5000 volts for all loads, the excitation has to be adjusted very considerably. The characteristic might therefore be plotted with variation in exciting current from no load to full load, to maintain constant terminal potential difference. The characteristic would then appear as in Fig. 161. The excitation regulation is the percentage increase in excitation required to maintain a constant terminal potential difference from no load to full load.

With machines of type (1) the percentage variation is large, and if the outside circuit be inductive, such as when running on a motor load, it is difficult to maintain an approximately constant terminal potential difference. The advantage would therefore appear to lie with machines of type (2). Many more machines, however, are being made of type (1), and therefore they must have advantages which outweigh the disadvantage of inferior regulation.

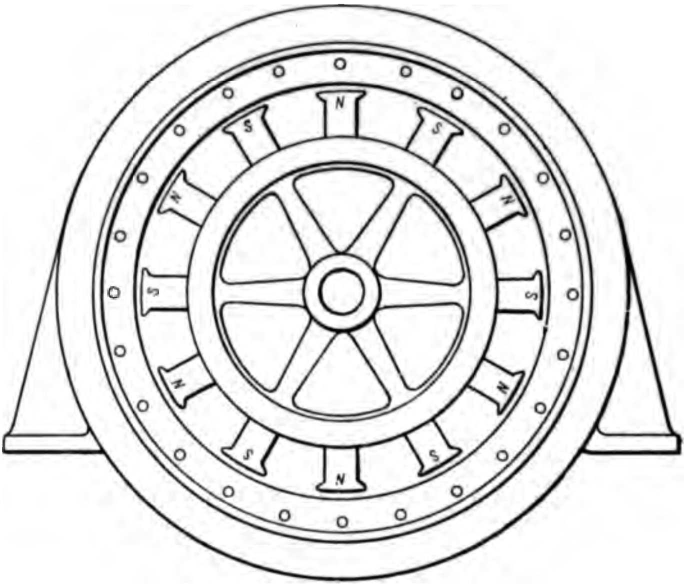

FIG. 159.

One of the great advantages attending machines of type (1) is the impossibility of dangerously overloading them, owing to their high inductance. In many cases, even on dead short-circuit the current cannot rise to more than 50 or 75 per cent. above the

[redacted]

full-load current. We have seen (p. 56) that an alternating current is impeded by two factors which add together vectorally, the impedance being equal to $\sqrt{R^2 + (2\pi nL)^2}$. The resistance of the armature circuit is usually very small, but the reactance voltage rising with the current, is sufficient to keep the latter within the safe value even when short-circuited. With this type the design is also more economical in the amount of copper required, and the conductors are supported by a much better mechanical

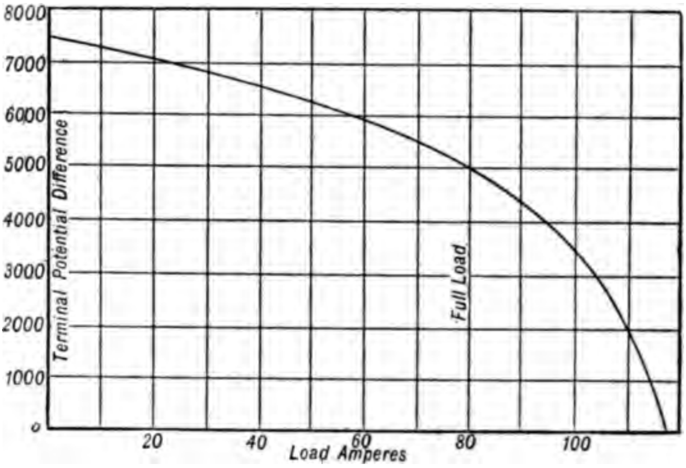

FIG. 160.

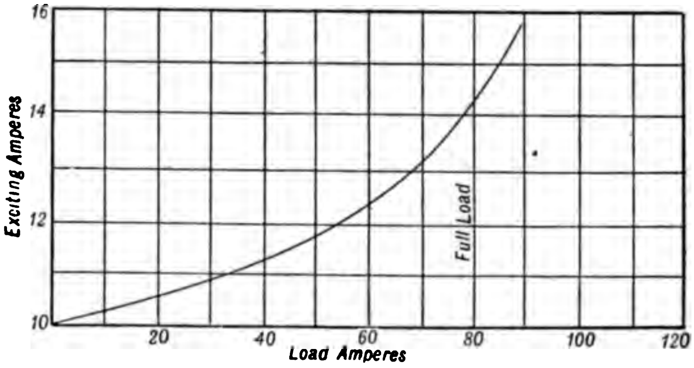

FIG. 161.

[redacted]

construction. In fact, the whole design is mechanically superior to machines of type (2).

Owing to regulation considerations, however, it is usual to design such machines so that the short-circuit current, with normal excitation, is two or three times the full-load current, for dead short circuits are things of very rare occurrence, and even then are usually provided against by over-load circuit breakers.

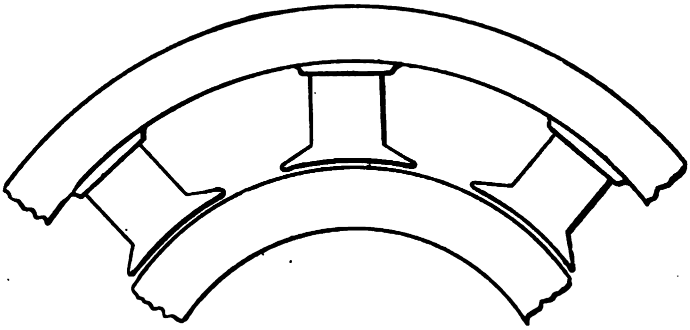

FIG. 162.

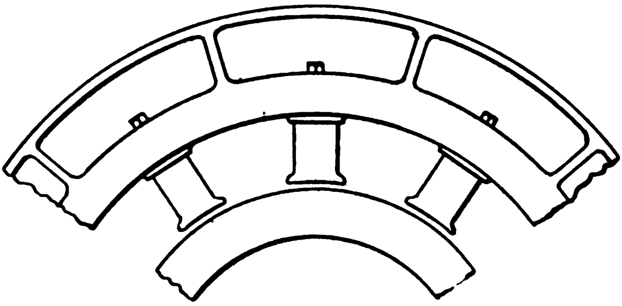

FIG. 163.

For the above reasons the armature winding is now almost exclusively wound in slots on an iron core, the inductance being a very variable quantity, owing to the varying number of turns per coil and the width and depth of slots employed. With the field coils fixed radially inwards, and a revolving armature, the carcase approximates in appearance to the multipolar direct-current frame, which we considered in Chapter X. The *most noti*ceable differences between the two are the absence of the commutator and the altered ratio of pole arc to pole pitch, which we have seen should not be more than 50 per cent. for the single-phase alternator, in order to avoid differential action, whereas with the direct-current machine it is usually between 65 and 70 per cent. (see Figs. 162 and 163).

In the majority of alternators, however, the arrangement is reversed. The armature conductors are wound in slots on the inside face of the laminated core, while the field-magnet system is built up on the rim of a massive fly-wheel, which revolves within the bore of the armature laminations, as shown in Fig. 164. Used in this way, the field-magnet system often takes the place of the fly-wheel in the ordinary engine and dynamo set, and is found to give excellent results. With the fly-wheel at one end of the shaft, and the armature at the other, the whole of the energy stored in the fly-wheel available for keeping an even peripheral speed of the armature with sudden changes in the load, has to be transmitted through the shaft, producing large torsional strains in it which are entirely avoided in the fly-wheel type of field. The armature insulation can be maintained much better with stationary winding than is possible when it revolves at a high peripheral speed, and there is also more space available for the winding and insulation, and the ventilation is better. By winding the coils on

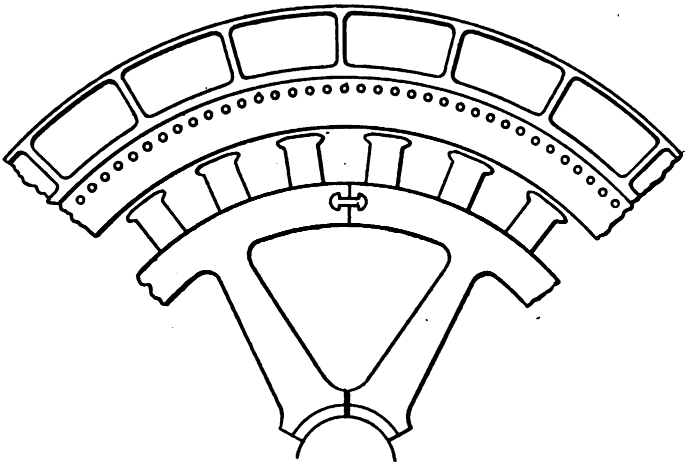

FIG. 164.

formers, and dropping them into position in the slots, the insulation can be made to withstand very high pressures, though machines for extra high pressure are often wound by hand by threading the conductors through micanite tubes fixed into the slots and projecting some distance on either side of the core. The pressure in the field-exciting circuit is small in every case compared

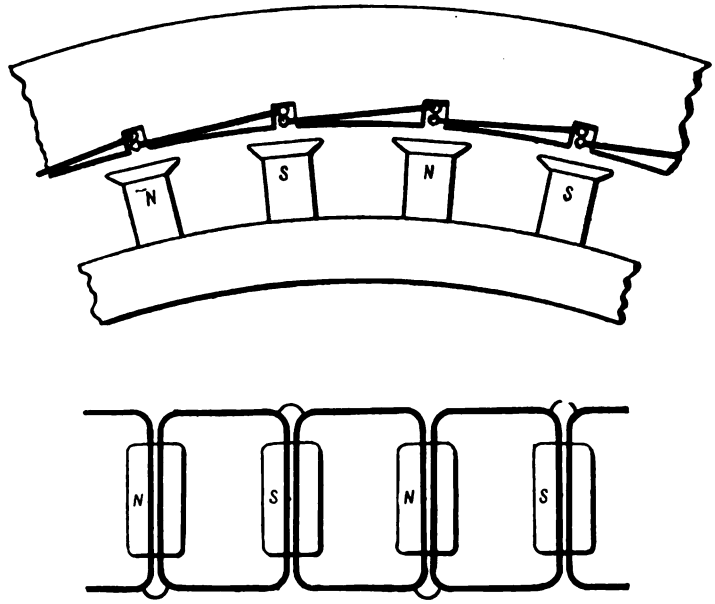

FIG. 165.

with that induced in the armature winding, and it is certainly much better to have the high-tension circuit stationary, and the brushes and slip rings necessary for leading the current into and out of the moving part, connected with the low-tension exciting circuit.

If the winding be placed in a single slot per pole, each conductor will have its maximum or minimum value at the same time, and consequently the value of the total electromotive force induced per pair of poles will be $= \frac{2{\cdot}22\text{NCS}}{10^8}$, N being the flux per pole, and C the total number of conductors in series, provided the distribution of the flux is such as to give rise to a sine wave of electromotive force. This is shown diagrammatically in Figs.

[redacted]

165 and 166, which represent two different methods of winding. In the first the winding is divided into two small coils, while in the latter, only half the number of coils, each with twice the number of turns, occupy the same winding space in the slots. There is a difference in the inductance of the winding in the two cases, that in Fig. 165 being only half what it is in Fig. 166, for the inductance varies with the square of the number of turns. There being only half the number of turns to each coil in Fig. 165, the inductance per coil will be $(\frac{1}{2})^2 = \frac{1}{4}$ of that of a coil in Fig. 166. But there are twice as many coils in series in one case as in the other, and therefore the inductances will be proportional to $\frac{1}{4} \times 2 : 1$, or $\frac{1}{2} : 1$.*

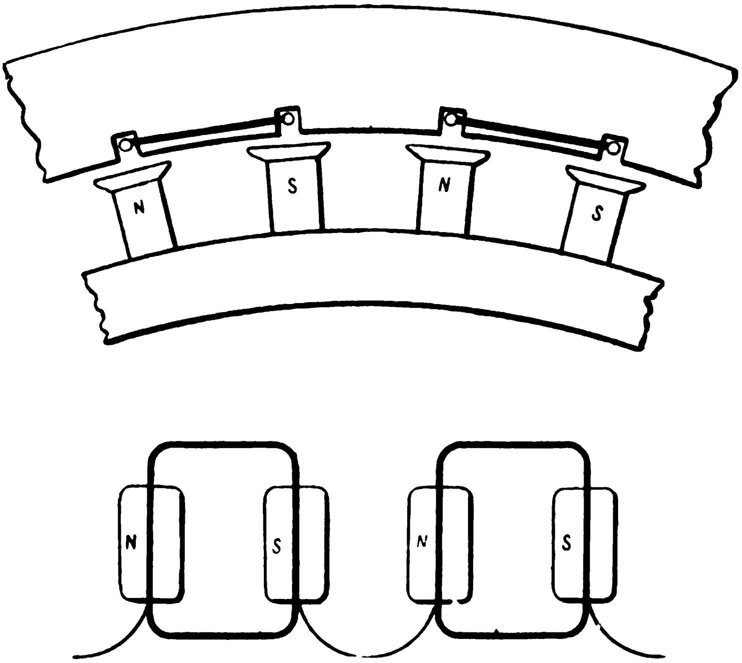

FIG. 166.

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* In practice, the inductance of ordinary winding is found to be greater than half that of hemitropic winding, probably due to the assumption that the leakage lines of each coil interlink with that coil only.

In either case, very little of the winding space is utilized, and therefore a much larger output from the same carcase is possible. We might put conductors into more slots per pole, and increase the output considerably, but not proportionally, as we shall see.

Suppose we wind four slots per pole—this being about the maximum number used in single-phase machines, though it is very common to find six slots per pole in the armature core, in which case two would be left empty—a great variety of windings may be employed. We might wind four separate coils of equal or unequal pitch, and connect them in series all round to form one coil per pair of poles, occupying eight slots, as shown in Figs. 167 and 168. This is known as "hemitropic" winding. We may also wind them so as to form two coils per pair of poles, of equal or unequal pitch, as shown in Figs. 169 and 170, and this is, perhaps, the more usual practice, for with it there is less overlapping at the ends, and the inductance of the winding is less than with the former method. The mean length of one turn is also considerably less, and therefore there is a decided saving in the amount of copper required. This is known as "ordinary" winding.

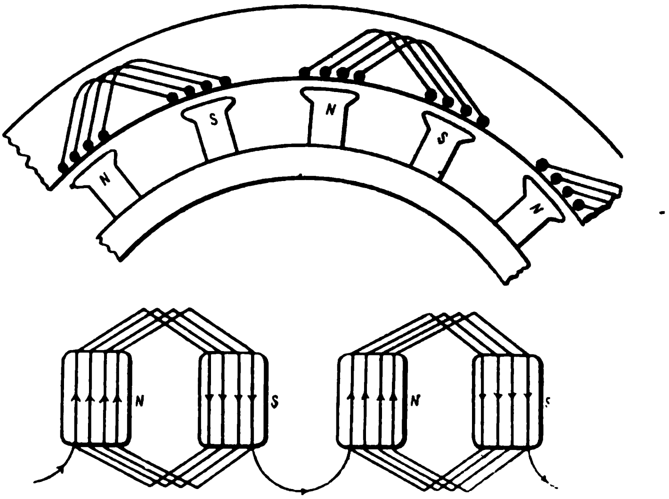

Fig. 167.

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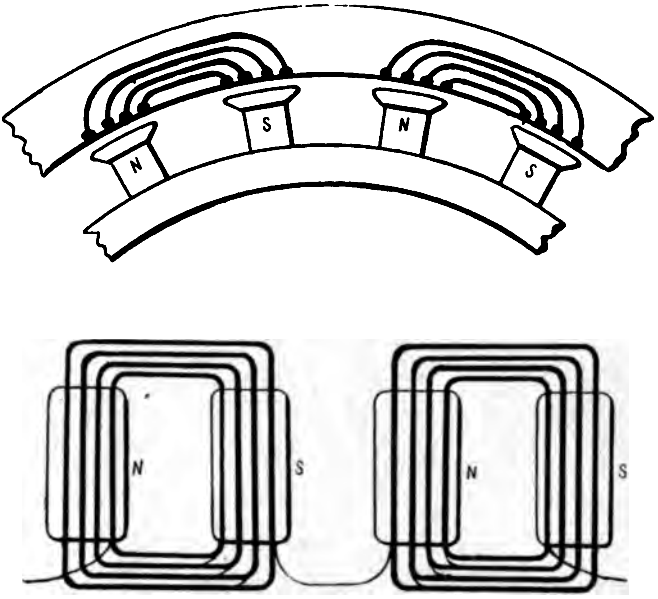

FIG. 168.

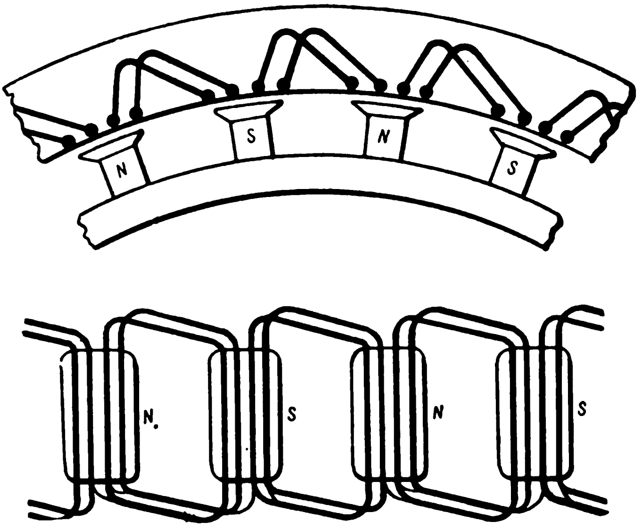

FIG. 169.

[redacted]

When the conductors take the form of stout copper bars, they are connected together by copper strips on the sides of the armature face, in one of many possible ways, some of which are shown, for a small number of poles, and in extended form, in Figs. 171–173. Alternators being machines specially suited for generating high voltages, the winding usually takes the form of coils of more than one turn, either wound by hand or on formers. The latter is much easier and quicker, and if care be taken in putting them in the slots, and the insulation of the slot is carefully made and finished off, such a winding should be able to withstand any pressure commonly employed. As we have already mentioned, the one point in favour of hand-wound coils is that they can be threaded through seamless tubes of micanite, or other insulating material, and so get excellent insulation between coil and core, but there is the possibility of injuring the insulation on the wires in threading them through, and in case of a short circuit on a coil the work involved in replacing it is great compared with the former-wound coil.

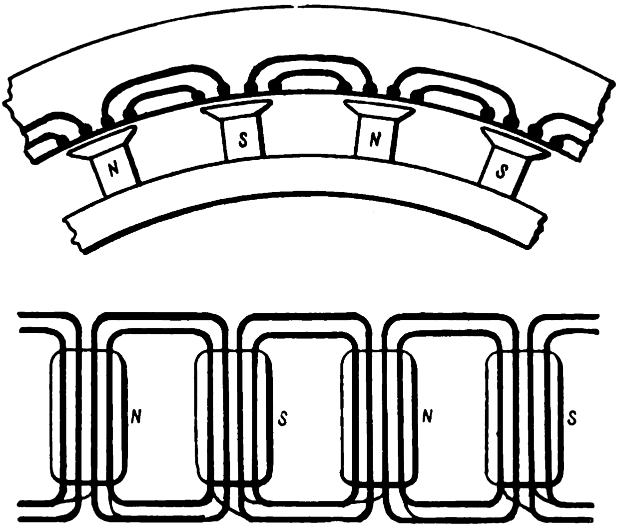

FIG. 170.

When the winding is distributed into more than one slot per pole, the various sections of each coil will be developing different

[redacted]

electromotive forces at the same instant, for one will have a maximum value at a different time to the others. The formula for the electromotive force of an alternator must therefore contain a factor depending on the distribution of the winding. The pitch of the machine, *i.e.* the distance from a line passing through the centre or axis of one pole, to a line passing through the axis of the next, represents electrically 180°, for a conductor, in moving a distance equal to the pitch, will generate half a cycle of electromotive force. If we have 6 slots per pole, and each coil occupies, say, 4 slots, then each section differs in phase by $\frac{1}{6}$ of 180°, or 30°. The electromotive force developed by one section per pair of poles will be $\frac{1}{4}\left(\frac{2{\cdot}22\text{NCS}}{10^8}\right)$, where N = flux per pole, and C the total number of conductors per coil. The total electromotive

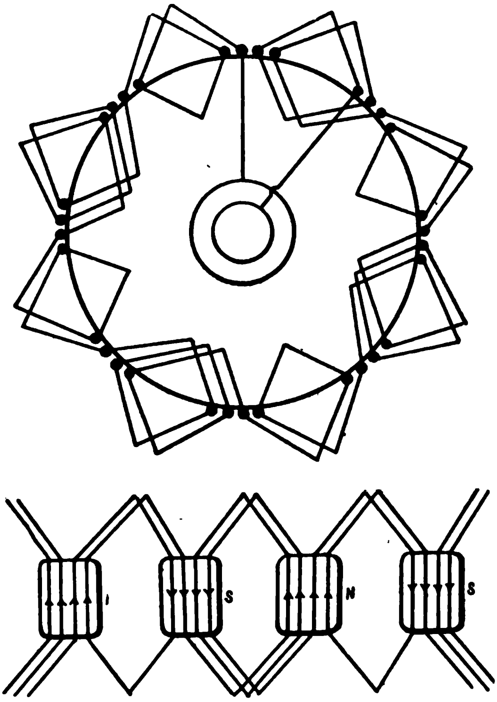

FIG. 171.

force of the coil will therefore be the resultant of four such electromotive forces, differing in phase by 30°.

Let *ab*, *ac*, *ad*, *ae* (Fig. 174) represent the four electromotive forces, each equal to $\frac{1}{4}\left(\frac{2{\cdot}22\text{NCS}}{10^8}\right)$, and each differing by 30°. The resultant of *ab* and *ac* will be *af*. The resultant of this and *ad* will be *ag*, and the resultant of *ag* and *ae* will be *ah*, which gives us the combined voltage of the coil. It will be noticed that *ah* must always be less than the sum of the components, and that the resultant is obtained, in every case, by placing the components end to end in their respective phase direction, and closing the figure by joining the extreme ends, the closing line being the resultant of the whole. The disadvantages attending distributed *winding* are (1) lower electromotive force with the same number

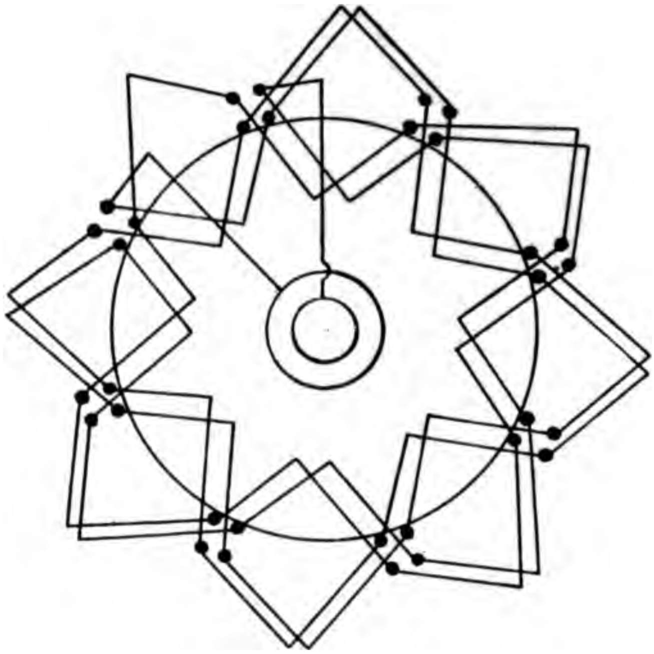

FIG. 172.

[redacted]

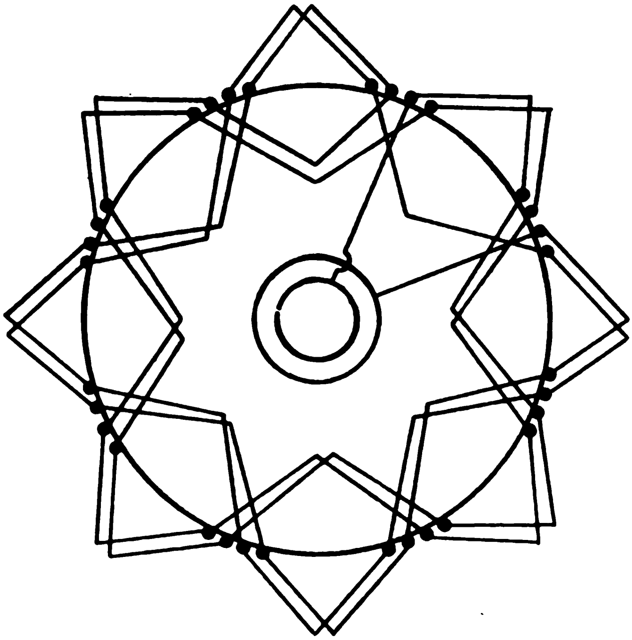

FIG. 173.

of turns; (2) machine larger in size and weight for a given output, therefore more expensive; (3) greater number of crossings of coils at the ends, therefore more difficult to insulate. On the other

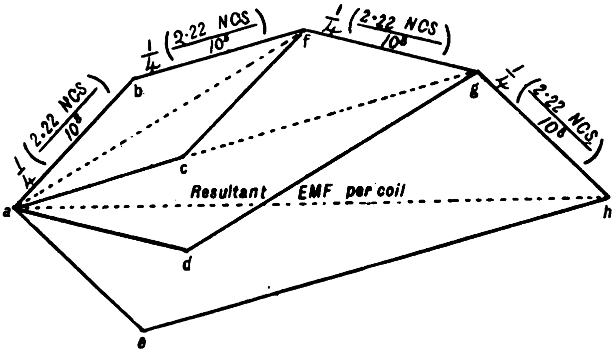

FIG. 174.

hand, the inherent regulation of the machine and the ventilation of the winding are greatly improved.

The electromotive force is further reduced by distributing the field flux, or by increasing the ratio $\frac{\text{pole arc}}{\text{pole pitch}}$. Taking a ratio of $\frac{\text{pole arc}}{\text{pole pitch}} = 0{\cdot}5$, which, as we explained earlier, is the usual practice with single-phase machines, and assuming the pole pieces to be shaped so as to develop approximately a sine wave of electromotive force in the winding, as in Fig. 175, the effective value of the electromotive force induced will be equal to the maximum value M multiplied by $\frac{1}{\sqrt{2}} = \text{M} \times 0{\cdot}707$. Now, suppose the ratio $\frac{\text{pole arc}}{\text{pole pitch}}$ to be reduced to 0·25, with the same value of total flux, we should get a peaked curve with a maximum value nearly equal to twice the former, for the rate of cutting (as the the coil sweeps past the pole at the same rate) will be nearly doubled. The curve obtained would probably be somewhat of the shape shown in Fig. 176, the effective value of which will be considerably greater than in the former case, probably 1·3, or 1·4 times as great. It will therefore be seen that another factor must come into the electromotive force formula, depending on the ratio $\frac{\text{pole arc}}{\textit{pole pitch}}$, or on the form factor.

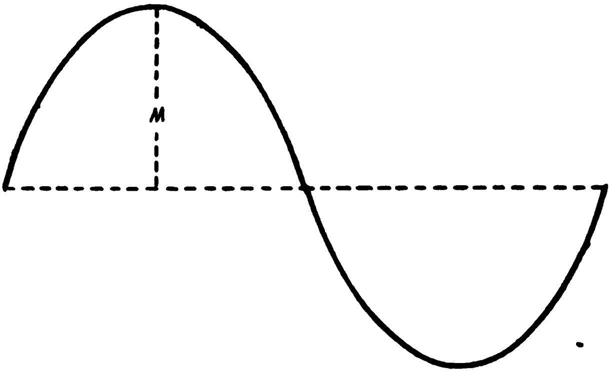

FIG. 175.

Usually the distribution factor and the form factor are combined in one constant multiplier, and we get for the electromotive force per pair of poles—

$$E = \frac{NCS}{10^8} \times K$$

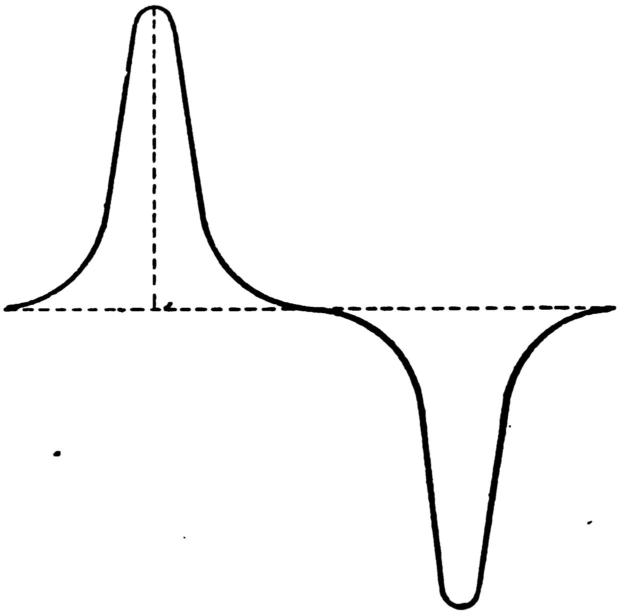

FIG. 176.

and for the whole machine—

$$E = \frac{NCS}{10^8} \times K \times p$$

where p represents the number of pairs of poles, C the total number of conductors in series, and K the values given in the following table for different windings and ratios of $\frac{\text{pole arc}}{\text{pole pitch}}$.

Pole arc / pole pitch	Width of armature coil / pole pitch	Values of K.
1 0	0·25	1·75
1·0	0·5	1·63
1 0	0·75	1·46
1·0	1·0	1·16
0·66	0·25	2·30
0·66	0·5	2·1
0·66	0·75	1·85
0·66	1·0	1·5
0·5	0·25	2·5
0·5	0·5	2·3
0·5	0·75	2·1
0·5	1·0	1·6

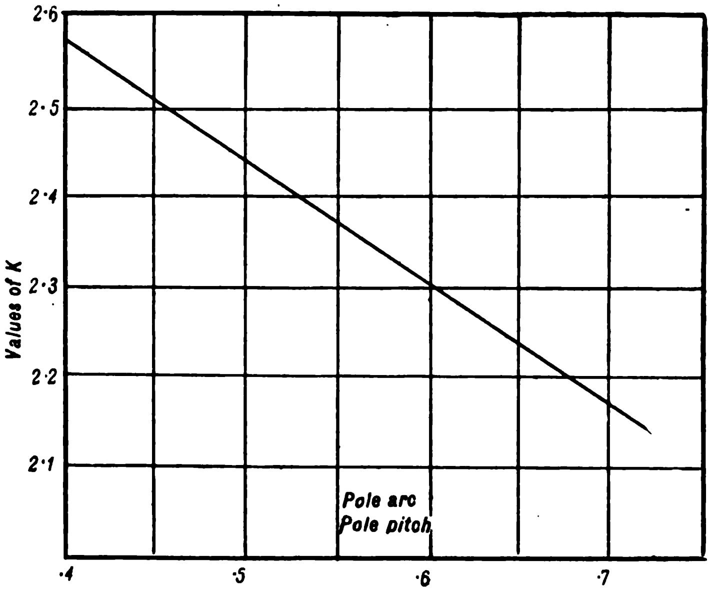

FIG. 177.

The above are values based on Mr. Kapp's figures, and have been found to accord fairly closely with the actual values obtained under test, though these values are altered considerably by different shaping of the pole shoes, which alters the form-factor still further. Müller gives the values in the curve (Fig. 177)

[redacted]

for an air-gap length of $\frac{1}{60}$ pole pitch, with the tips well rounded, and for coils quarter the width of the pole pitch.

Consider the diagram (Fig. 178). The coils are here shown in the mid-pole position, in which place they are cutting lines of force at the maximum rate, and are therefore developing their maximum electromotive force. Suppose the outside circuit to be closed, and a current flowing through the machine. If the circuit were entirely non-inductive, the maximum value of the current would come at the same instant as the maximum value of electromotive force, for the two will be exactly in phase. The armature current will give rise to a cross flux, exactly as in the case of the direct-current armature, as shown in Fig. 179, strengthening the trailing, and weakening the leading pole tip, for though the poles are changing continuously in respect to the coils, the current in the latter changes also in step with them.

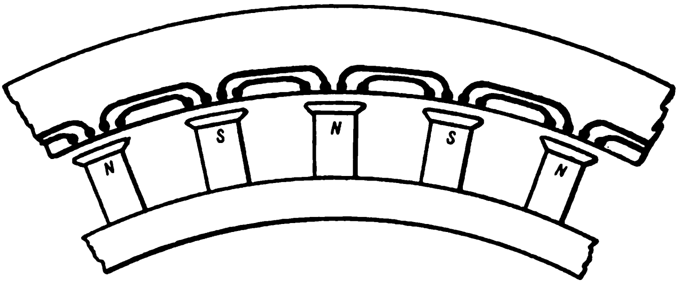

FIG. 178.

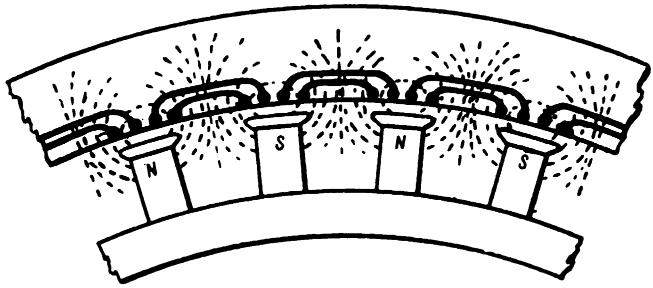

FIG. 179.

This distortion of the lines produces a greater density in the trailing pole tip, and also a greater mean length of line across the air gap, and therefore the total flux and the electromotive force induced may possibly be decreased slightly, due to this.

It will be seen, however, that the current in the machine can never be quite in phase with the electromotive force, for if the outside circuit were perfectly non-inductive, the armature circuit will not be so. In fact, we have mentioned machines in which the inductance is so high as to make them safe even on short circuit. On the other hand, with machines whose armature winding is built up on porcelain or laminated brass cores, the inductance is very small compared with the slotted iron-cored type, and consequently the angle of lag of the current behind the electromotive force is, with them, very small, unless the inductance of the outside circuit be large.

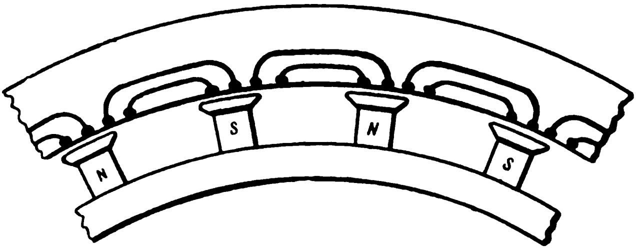

Fig. 180.

Owing to the lag of the current behind the electromotive force, the position of maximum current will come at a time when the electromotive force has died down to some lower value, *i.e.* when the mid-pole position of the field has advanced beyond the mid-coil position, as shown in Fig. 180. The armature ampere turns now exert a certain demagnetizing effect on the pole, and also give rise to an increased leakage coefficient, and the larger the angle of lag between electromotive force and current the greater will be these effects. Fig. 181 shows the case where the power factor of the circuit is extremely low, so that the angle of lag is nearly 90°. In this case the whole of the armature ampere turns are active in producing a demagnetizing magnetomotive force, which makes good pressure regulation difficult, if not impossible. Of course with strong field flux and weak armature ampere turns, these effects of armature reaction will be less.

The demagnetizing effect of the armature ampere turns is proportional to the sine of the angle of lag between the electromotive force and current, *i.e.* between the position of maximum current and the mid-pole position for the armature coils; thus, suppose we have 50 turns per pole on the armature face, and at a certain time, when the angle of lag is 30°, the current in the conductors happens to be 20 amperes. This current will have a maximum value of $\sqrt{2} \times 20 = 28$ amperes, therefore the maximum demagnetizing ampere turns per pole will be $= 50 \times 28 \times \text{sine } 30^\circ = 700$.

It will be noticed that it is only in the extreme case of power factor = 0 that the whole of the armatures are demagnetizing, and we have seen that, though it is possible in special cases to get very low power factors, it is impossible to get a value of zero. On the other hand, it will be noticed that in the majority of machines, working with a power factor in the external circuit of unity, there is a certain angle of lag in the machine on account of its own inductance, and therefore a certain demagnetizing action and an increased leakage coefficient. The effect of this in causing a drop in terminal potential difference often far exceeds the I.R. drop of the machine, in fact, the latter is, in most cases, quite negligible in comparison with the former. It will therefore be evident why the inherent regulation of machines with large inductance is poor compared with those having the opposite characteristic.

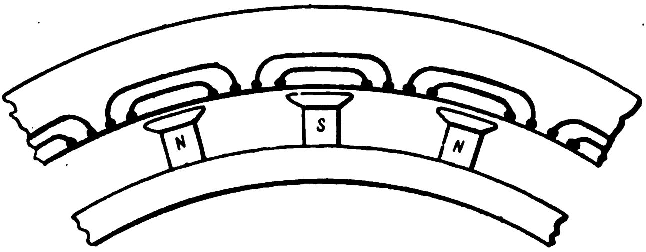

FIG. 181.

The inductance of machines of similar type varies considerably; a change in the shape or dimensions of the slots, the length of the air gap, the number of turns per pole, or the distribution of the winding often affecting it to a marked degree. Again, machines similar in every other respect vary in the length of the armature, and therefore in the inductance per turn. To get a basis for comparing one machine with another, Messrs. Parshall and Hobart proposed the method, now generally followed, of specifying the inductance of alternators in terms of "lines of force per ampere turns per inch length of armature laminations." This reduces it to about the most simple case, for by this method machines varying considerably in the number of armature turns per pole, in the length of the armature, or in the current delivered are reduced to similar unit values.

As an example, suppose the length of the armature laminations in a particular case to be 10 inches, with three slots per pole and ten conductors per slot, making a total of thirty turns per pole; and, further, suppose the inductance of the complete coil to be 0·004 henry; then—

$$\left.\begin{array}{l}\text{Interlinkings of lines and turns of complete}\\ \quad\text{coil with a current of one ampere}\end{array}\right\} = 0{\cdot}004 \times 10^{8}$$

$$= 400{,}000$$

$$\left.\begin{array}{l}\text{The interlinkings of lines and turns of complete}\\ \quad\text{coil with one ampere for one inch length of}\\ \quad\text{the armature will be}\end{array}\right\} = \frac{400000}{10}$$

$$= 40{,}000$$

The inductance of a coil being proportional to the square of the number of turns, we have—

$$\left.\begin{array}{l}\text{Interlinkings of lines and turns for one ampere}\\ \quad\text{per inch length } \textit{for one turn}\end{array}\right\} = \frac{40000}{30^{2}} = 44$$

$$\left.\begin{array}{l}\text{Therefore the lines of force per ampere turn per inch}\\ \quad\text{length of armature laminations}\end{array}\right\} = 44$$

This figure varies in practice, depending on the depth of slots, the number of slots per pole, the distribution of the winding, whether the poles are solid or laminated, etc. For purposes of calculation where approximate results only are required it will serve to take the inductance measured in this way as being equal to thirty. Take the case of a machine designed for 50 amps. at 5000 volts, speed 240 revolutions per minute, 15 pairs of poles, therefore frequency = 60, and suppose the armature to be 10 inches long, wound with thirty coils of thirty turns each. The inductance per coil will then be equal to the lines per turn per

[redacted]

inch, multiplied by the length of the armature in inches, and by the square of the turns, or—

$$\text{average inductance per coil} = \frac{30 \times 10 \times 30}{10^8} = 0{\cdot}0027$$

$$\left.\begin{array}{l}\text{and therefore the average inductance of the}\\ \quad\text{whole armature}\end{array}\right\} = 0{\cdot}0027 \times 30$$

$$= 0{\cdot}081 \text{ henry}$$

Let us further consider the above machine. Suppose the resistance of the armature coils be 0·25 ohm, then the full-load I.R. drop will be $= 50 \times 0{\cdot}25 = 12{\cdot}5$ volts in phase with the terminal potential difference. The reactance volts at full load will be equal to $2\pi n\text{LI} = 2\pi \times 60 \times 0{\cdot}081 \times 50 = 1527$ volts, lagging by 90°. The total electromotive force to be generated at full load will therefore be the vectoral sum of the no-load voltage plus the armature I.R. drop and the reactance voltage. The generated volts at full load will be $\sqrt{5012^2 + 1527^2} = 5239$ volts.

Let us suppose that 4000 ampere turns per pole are required to produce the no-load electromotive force, with unity power factor in the external circuit; then, owing to the reactance of the armature, there will be a demagnetization effect at full load proportional to the sine of the angle of lag between the current and the electromotive force.

The tangent of the angle of lag will be $= \frac{1527}{5012} = 0{\cdot}29 =$ tangent of 17°.

The armature ampere turns per pole at full load will be $= 50 \times 30 = 1500$, and the maximum value will be $1500 \times \sqrt{2} = 2121$ ampere turns. The demagnetizing effect of these, proportional to the sine of the angle of lag, is therefore proportional to the sine of $17° = 0{\cdot}29$, so that the demagnetizing ampere turns per pole at full load with unity power factor in the external circuit $= 2121 \times 0{\cdot}29 = 615$, and the exciting ampere turns $= 4615$.

The same can be worked out for other loads, and the characteristic curve plotted.

With a lower power factor in the external circuit there will be a larger angle of lag between the current and the electromotive force in the machine, and consequently the demagnetizing ampere turns will be increased.

The values corresponding to various power factors may be

[redacted]

found graphically in the following manner: Set out a vector to represent the terminal volts plus the I.R. volts to any convenient scale, as represented by OA (Fig. 182). Draw a vector at right angles, to the same scale, to represent the reactance voltage OB; then the angle OAB represents the angle of lag for a power factor of unity in the external circuit. For a power factor of, say, 0·8, the cosine of the angle of lag = 0·8, and therefore the angle of lag = 36°. Set off from O a line OC equal to OA, but making an angle with it of 36°, and join CB. The angle ODB is then the angle of lag in the armature conductors for a power factor of 0·8 in the external circuit. OD can be scaled off, and $\frac{OB}{OD}$ is the tangent of the angle of lag.

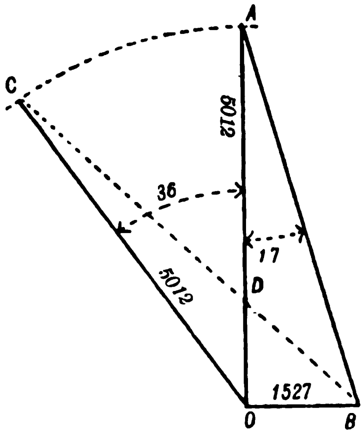

FIG. 182.

In the case we have been considering, OB = 1527 and OA = 5012, the angle OAB = 17°, OD will be = 1300, and therefore the tangent of the angle of lag = $\frac{1527}{1300}$ = 1·17 = tangent of 49°. The sine of 49° = 0·75, and therefore the demagnetizing ampere turns per pole at full load with power factor of 0·8 = 2121 × 0·75 = 1590, and therefore the exciting ampere turns required for full-load power factor of 0·8 = 4000 + 1590 = 5590.

Messrs. Parshall and Hobart, to whom the foregoing method of predetermining the characteristic is due, have made a large series of experiments to determine the value of the inductance in terms of lines per ampere turn per inch for all the various modifications met with in practice, both in single and polyphase current machines, a detailed account of which will be found in their work entitled "Electric Machine Design." From the results of these experiments it was found that the inductance of coils in open slots with the armature clear of the pole pieces varied with the depth of the coil in the slot. For three positions of a coil (*with a* depth equal to half that of the slot), viz. just outside, halfway down, and at the bottom, the inductance of the embedded portions were in the proportion of 6·6 : 10·7 : 18·3.

With a certain winding arranged in from one to six slots, all having the same ratio of width to depth, the inductance of the embedded portion was as represented in the curve (Fig. 183), showing that even with such distributed winding as six slots per pole the inductance is still 45 per cent. of what it would be if wound in a single slot.

The position of a coil when it has its maximum inductance depends in part on whether the pole pieces are solid or laminated.

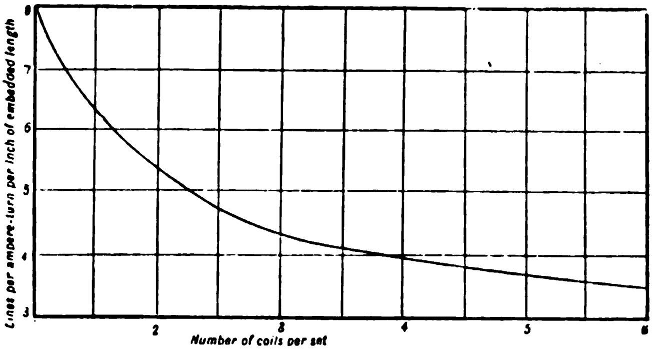

FIG. 183.

With solid pole pieces the position of maximum inductance is usually when the sides of the coils are near the mid-pole face position, for eddy currents induced in the pole faces prevent any large interlinking of the armature flux with the main magnetic circuit. With laminated poles, however, the position of maximum inductance is sometimes 90° removed from the mid-pole face position. The inductance with solid poles is in every case less than with laminated poles, other things being the same.

Taking these various points into consideration, the values of lines per ampere turn per inch of the embedded portion are given for single-phase machines, thus—

For coils of small breadth on the surface . . .	0·5
For coils with breadth equal to pitch on the surface	2·5
Unislot coils in open, straight-sided slots . . .	7·6 to 15

Thoroughly distributed winding in open, straight-sided slots	3·8 to 7·6
Unislot winding with closed-over slots . . .	18 to 36
Distributed winding with closed-over slots . .	7·6 to 15

For the free portion (whose length per turn is usually about three times the pole pitch) the value 1·25 lines per ampere turn per inch has been found to be sufficiently near for most purposes.

All the various causes of voltage drop under load are often grouped together under one head, called the "synchronous impedance" of the machine. This represents such an impedance which, when connected to an electromotive force equal to the open circuit electromotive force, allows a current to flow equal to that which flows through the machine. This can very easily be determined experimentally in the following manner:—

Having taken off all excitation, short-circuit the machine through an ammeter, and place a voltmeter across its terminals. Run the machine at its normal rated speed, and slowly adjust the exciting current till the ammeter reads the full load or any other current desired. Now open the ammeter circuit, and read the value of volts generated. The volts generated divided by the current is known as the synchronous impedance. It will be noticed that the voltmeter will indicate no voltage, while the outside or ammeter circuit is closed, for the power required to urge the current through the ammeter is a perfectly negligible quantity, and therefore while the current is flowing the whole of the electromotive force generated is expended in urging the current through the machine, against its own reactance principally, for we have seen that the effect of the armature resistance, when added vectorally, is almost negligible in most cases.

For good regulation, especially on inductive loads, the field excitation should be strong, *i.e.* the saturation of the iron should be taken well over the bend in the magnetization curve. The no-load excitation characteristic, sometimes called the "no-load saturation curve," should be a line following closely the magnetization of iron curve, though it is usually found that the bend, or knee, is more rounded, owing to the different parts of the circuit reaching the saturation point at different times, and to the constant permeability of the air gap. This curve, giving the relation between the terminal potential difference and the exciting ampere turns

[redacted]

for no load is shown in the top curve of Fig. 184. A full load excitation characteristic for unity power factor is shown in the lower curve on the same diagram. In the latter, with zero-potential difference, the excitation is such as to maintain the full-load current in the armature conductors against its reactance; that is to say, at this point the armature is dead short-circuited through an ammeter, and therefore the terminal potential difference must be zero. The current is maintained at full load for all positions on the curve by adjusting a non-inductive resistance in the armature circuit up to the full excitation.

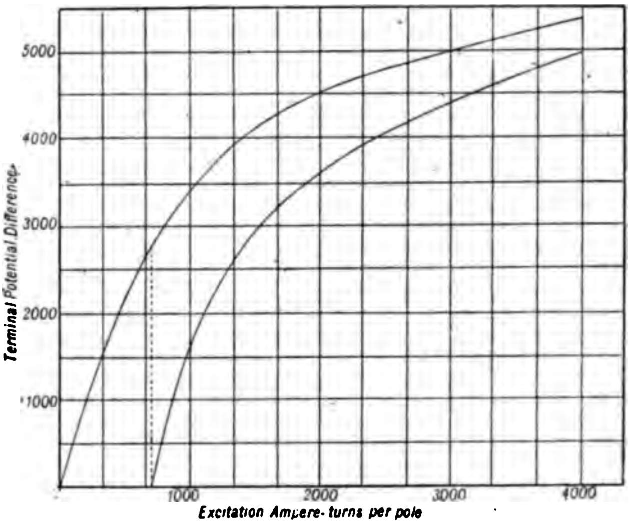

FIG. 184.

These curves indicate the point on the magnetization curve at which the machine is normally excited, and also the change in terminal potential difference in throwing on and off the full load, which, it will be noticed, is less if the normal excitation is well over the bend. With a weak normal excitation, the inherent regulation would be very inferior, and worse still with an inductive load.

The watts expended in the exciting circuit are usually about 2 per cent. of the machine output in large-sized alternators, while in small sizes up to, say, 20 kw. it often runs up to about 4 per cent. Owing to the extra cooling due to the fanning action of the revolving fields, and the larger amount of surface exposed, the heating limit is higher than in multipolar direct-current machines, or in alternators with fixed field coils and revolving armatures. The limiting value of cooling surface, for a temperature rise of 35° C. is from 1 to 2 watts per square inch, while for stationary field winding it is not more than half this amount.

CHAPTER XIII

CONSTRUCTION OF ALTERNATORS

Two different types of alternators have been mentioned, viz. those with large and those with small reactance. The armature winding of the latter is commonly made in the form of flat coils by winding copper strip round some former or frame of non-magnetic material. A large series of these coils are then mounted on a suitable wheel or spider, and revolved between the pole pieces of a number of field magnets, with opposite poles facing, arranged round the face of two cast-iron yoke rings. Notable machines of this type are those designed by Mr. Ferranti for the London Electric Supply Corporation, generating a pressure of 10,000 volts. Mordey, Crompton, and several others have designed similar machines, some with a single coil for magnetizing the whole of the field poles. We shall refer to this method of excitation later. These machines are interesting in many ways, but they have weaknesses which have prevented their extended use. The standard alternator at the present time is of the fly-wheel, revolving-field type, represented diagrammatically in Fig. 159, the construction of which we shall consider first.

In the larger sizes it is the usual practice to cast the fly-wheel, to which the field cores are fixed, in several pieces, depending on the number of spokes, so as to prevent cooling strains, as explained on p. 167, in connection with the armature spiders of large multipolar machines. The spokes are often cast with double arms, to facilitate the fixing of the poles, by bolts through the rim. The various sections are then machined up at the joints, and locked together by massive steel keys shrunk into recesses cut in the face of the rim. At the boss a couple of stout steel rings are shrunk on to steps turned on either side (Fig. 185). In medium sizes, the parts, after machining on the faces, are bolted together (Fig. 186), while in smaller sizes the fly-wheel is often cast in one piece. In special cases, the necessary strength needed to resist

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centrifugal strains has resulted in the body of the fly-wheel being built up of rolled steel plates riveted or bolted together, and bolted to both the rim and the boss, which are made in separate *castings* (Fig. 187). In other cases the rim of the fly-wheel is

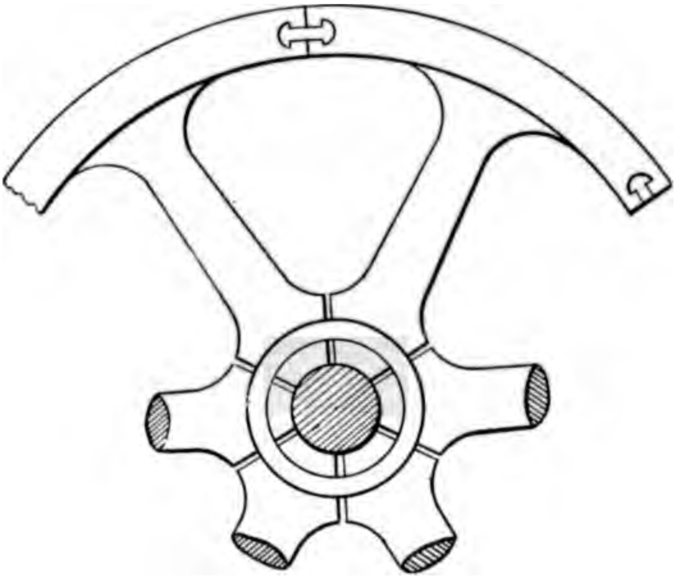

FIG. 185.

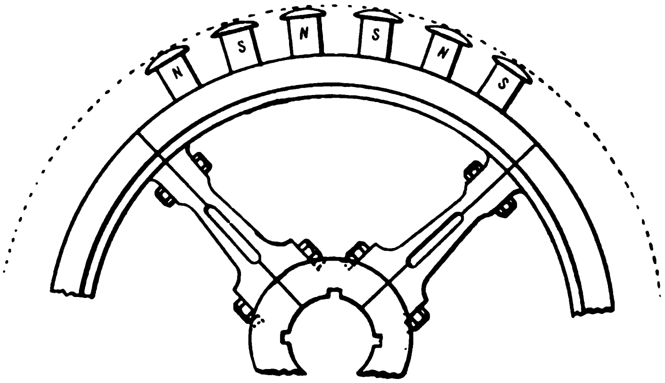

FIG. 186.

[redacted]

cast separately in steel sections, and bolted to projections on the ends of the spokes, the latter being thus free to contract separately in cooling (Fig. 188). In all cases the guiding principle is—apart from facilitating the work of casting—to get a structure which shall be massive enough to store a large amount of kinetic energy while serving as a good magnetic yoke for the field poles, and, at the same time, one that shall be free from internal stresses due to unequal contraction in cooling, and strong enough to withstand the high centrifugal strains which are brought about in such a mass revolving at a high circumferential velocity.

The field cores are often laminated throughout to prevent eddy currents due to any swinging of the field caused by armature reaction, and this often leads to special methods of support. It will be noticed that these are flying round at a high peripheral speed, and the centrifugal force tending to throw them off is thus very great. A perfect mechanical connection to the rim of the fly-wheel is therefore absolutely necessary. Where solid cores are used, it is considered necessary in most

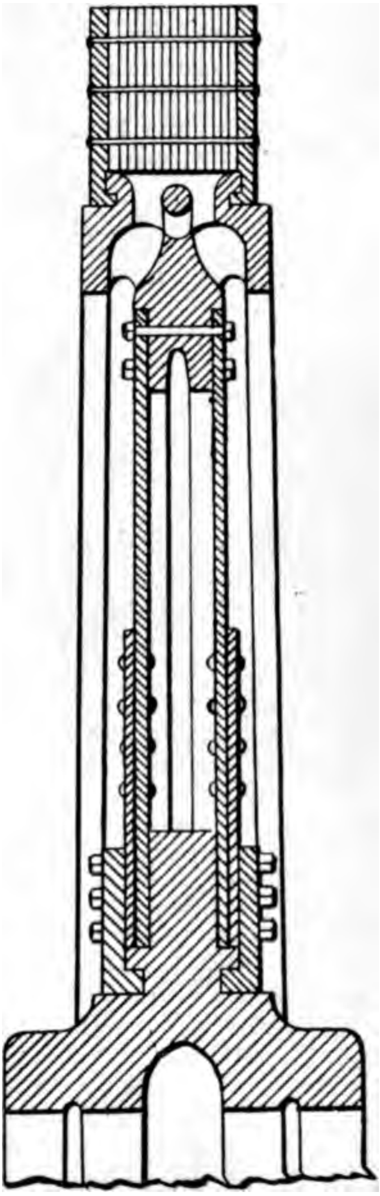

FIG. 187.

cases to laminate the tips for a good depth, for frequently there is considerable swinging or shifting of the flux at the pole face. Two methods of supporting the field cores have been given in Figs. 187 and 188. Three different methods adopted by Messrs. Dick Kerr and Co. are shown in Figs. 189 to 191, the first two showing laminated cores, and the third solid cores with laminated tips.

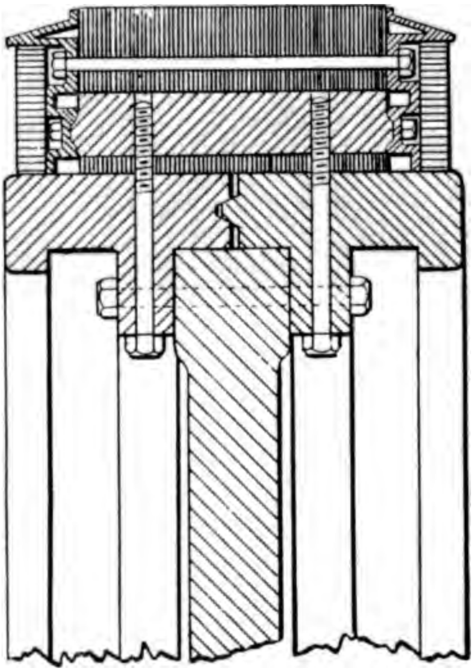

FIG. 188.

In some instances the field cores are cast in one piece with the wheel, in which case cast-iron pole shoes are usually screwed or dovetailed to the ends of the cores (see Fig. 192). The laminated field cores are also cast-welded to the rim in certain cases, as in connection with the yoke ring of multipolar direct-current dynamos. In fact, most of the methods of attachment explained in this connection have been adopted in fixing the field cores in alternators.

Perhaps the most common method of fixing laminated poles is that represented in Figs. 188 and 190, where a square bar of

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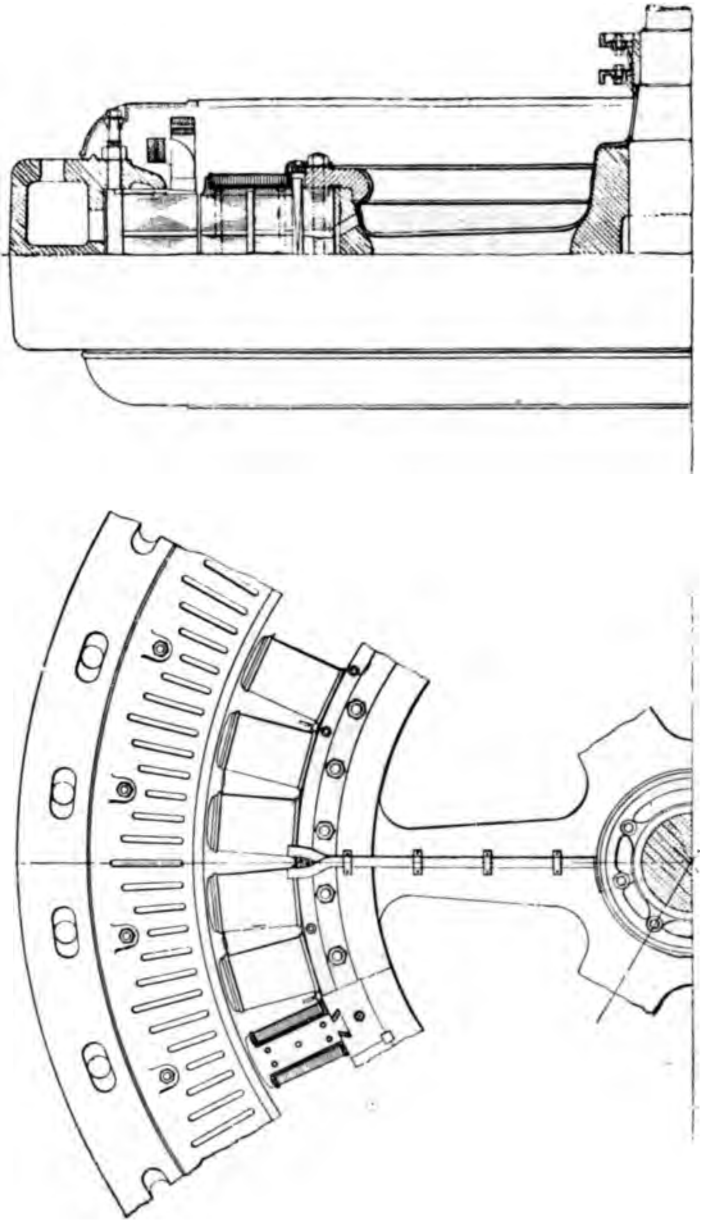

FIG. 189.

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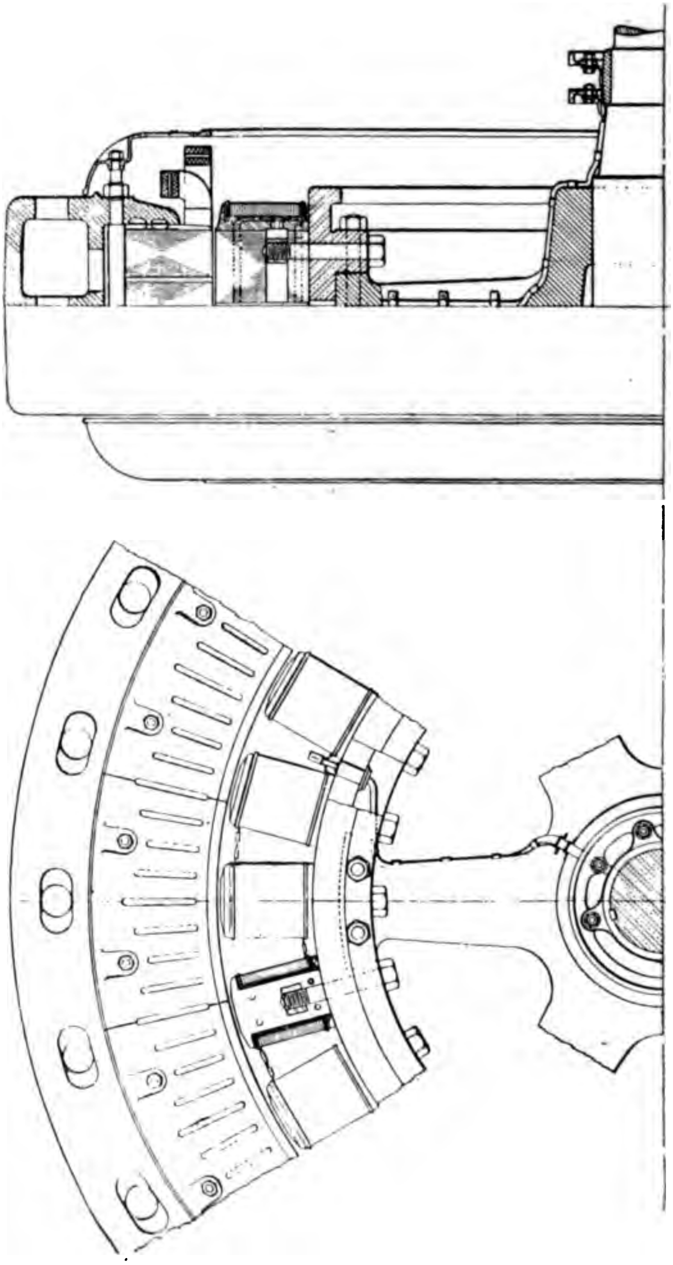

FIG. 190.

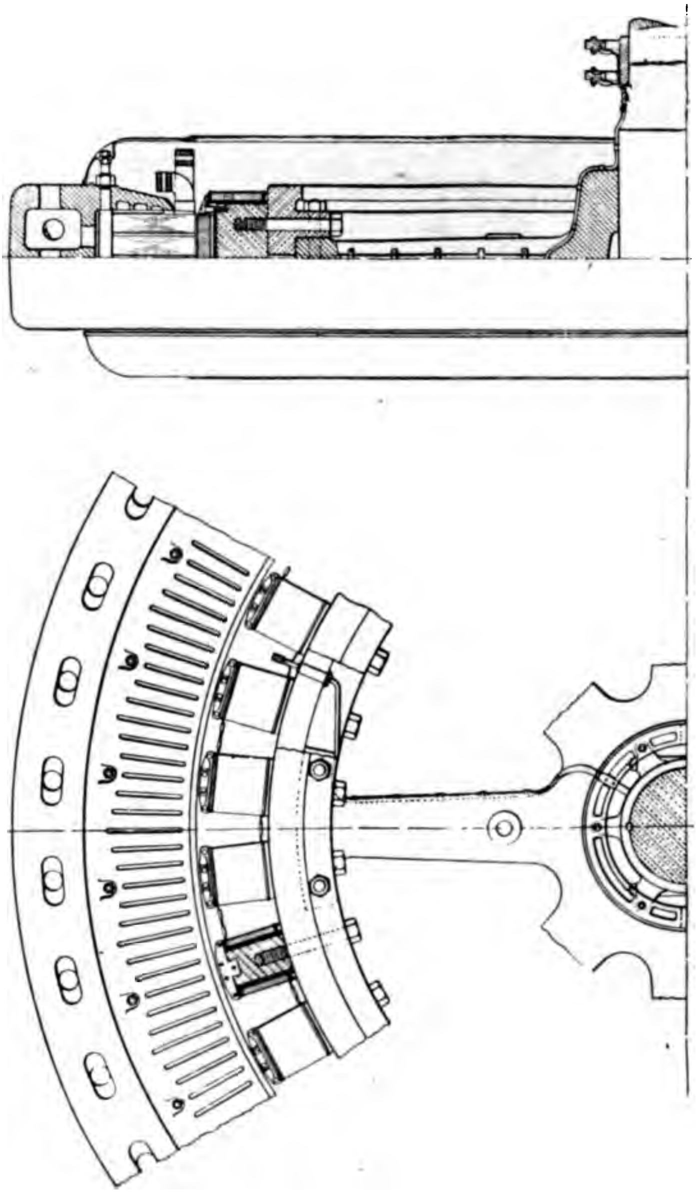

FIG. 191.

steel passes right through the plates, the holding-down bolts being screwed up into it.

The field coils have also to be very firmly fixed to the pole pieces, and they are usually held in position by the overhanging pole tips or pole shoes (see Figs. 189 to 192). When wire wound, the winding has to be very securely bound, for there is a tendency, not found in stationary field coils, for the turns to ride over each other, and bulge towards the outside. For this reason alone, flat copper strip wound on edge is preferable, and in the case of turbine-driven machines it becomes an almost absolute necessity. In the largest sizes, a sufficient number of turns cannot be got in

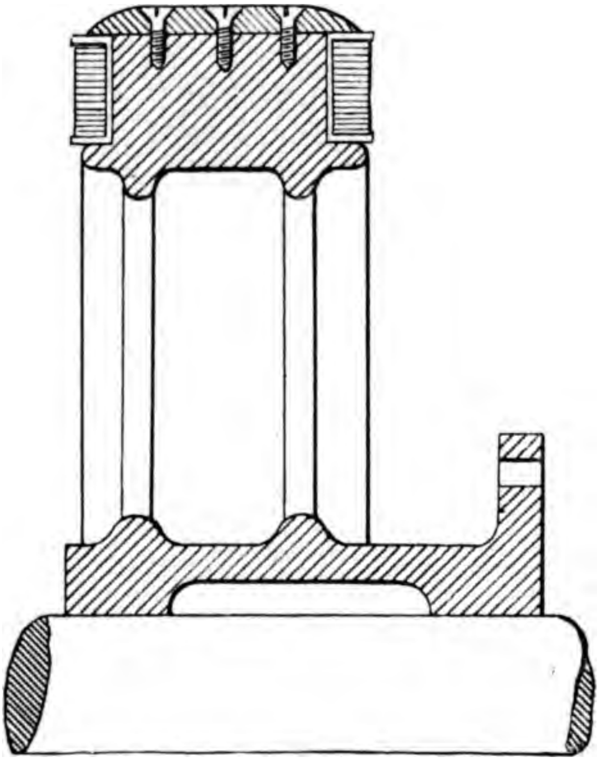

FIG. 192.

[redacted]

a single layer, in which case, two, three, or even four layers of flat-strip winding are put on with a small space between each for ventilating purposes.

The coil frame, or bobbin, is in some cases made of thin metal perforated at the ends to allow of better ventilation, and fixed to the core, with an air space on the inside, by bolts passing right through (Fig. 193).

The armature, laminations, or "stator-core plates," as they are sometimes called, are built up within a cast-iron case provided with a number of ventilating holes, so that air may circulate through to the back of the core plates. The case is usually made in two parts, but in the largest sizes is often made in four pieces for convenience in handling. These are then machined on the surfaces and bolted together. The case—which, when carrying the core plates and armature winding, is of great weight—should be designed to possess exceptional stiffness, otherwise there will be a slight deflection when it is fixed down with the whole of the weight thrown on to the two supporting feet. In some machines of large diameter it has been found necessary to provide an adjustable step at the lowest point, and also adjustable supporting feet, so that the case may be centred after erection. The inverted-box design, shown in Figs. 189 to 191, as made by Messrs. Dick, Kerr, & Co., is very common, giving about a maximum of stiffness for a given weight of metal; especially if well ribbed between the outer and inner walls.

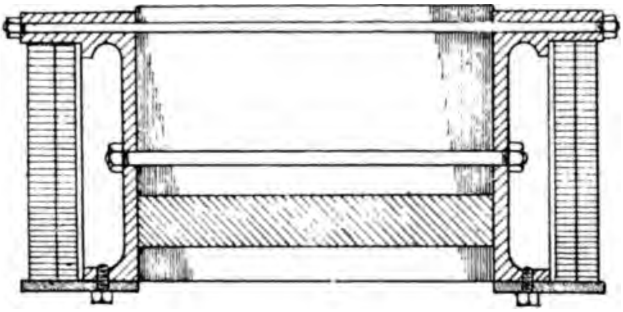

FIG. 193.

The case is frequently cast with a flange on one side, and the inside face of this forms one support for the core plates a second flange plate, cast separately in sections, engages in a groove on the other side of the case, and the core plates are rigidly held in place by a large number of bolts passing through the whole (see Figs. 189 to 191.)

Fig. 194, from designs by the Westinghouse Co., gives the section of a very stiff construction of stator case for a 5000 kw. machine. In this, both flanges are cast separately, and fit into grooves on either side of the case.

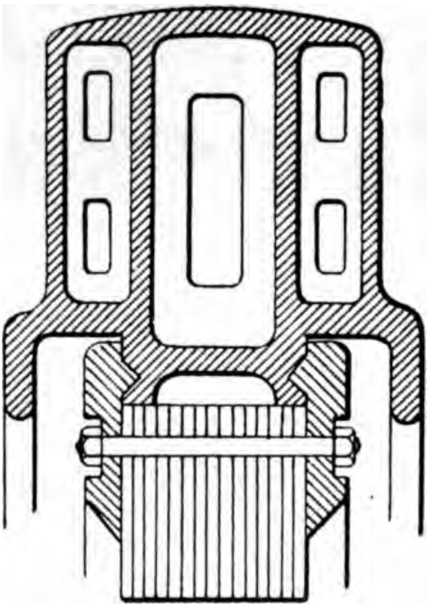

FIG. 194.

Fig. 195 shows quite a different type, made by the International Electrical Engineering Company, in which the stator case is cast in two parts, with continuous flanges on each side. These are machined on the inside faces and bolted together with a number of bolts passing through the flanges and core plates, heavier bolts also passing through the inside webs. Other Continental designs are shown in Figs. 196 and 197, and it will be seen that a great diversity in construction exists in this part of alternators, though the object is the same in each—viz. to get a very stiff case and a rigid support for the core plates with a minimum of weight.

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One Continental firm has adopted a light construction of case, and stiffened it by bracing it together with two sets of tie rods

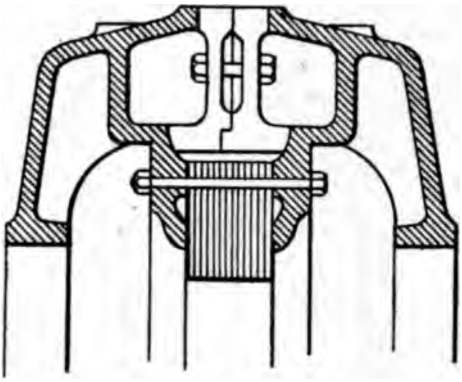

FIG. 195.

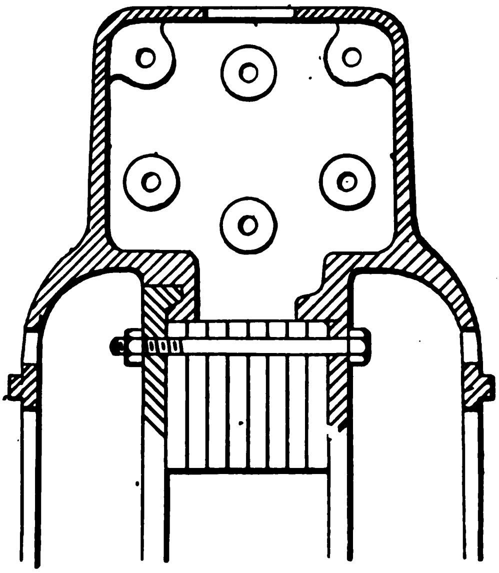

FIG. 196.

running tangentially right round the outer face. The core plates are, in this case, open to the air on their outer face for most of

[redacted]

their length, the case being more in the nature of end rings. This method, however, does not seem to be as satisfactory as a continuous cast-iron case of stiff design.

There is very little difference in the method of fixing the armature coils in the case of alternators from that employed in multipolar, direct-current dynamos. The coils are very frequently former wound and afterwards insulated. Some firms then bring the coils absolutely to the right shape by pressing them in hot formers, after which they are soaked in a special insulating compound and dried. As a rule, the insulation of alternator conductors has to withstand much higher pressures than that for direct-current machines; and the insulating of the armature coils is a point requiring exceptional care. It will be remembered that with any given effective electromotive force generated, the maximum value which the insulation has to withstand is $\sqrt{2}$ times greater. An alternator, therefore, generating an effective electromotive force of, say, 10,000 volts, has to withstand a maximum pressure in the armature coils of 10,000 × 1·414 = 14,140 volts. It is usual to test the insulation by applying to the coil an alternating pressure equal to twice the normal working pressure, and maintain it for, say, an hour. In the above case this would give a maximum testing pressure of 28,280 volts, which would soon disclose any weakness in the insulation. For these high pressures it is often necessary to dip and bake the coils separately ten or twelve times. They are then wrapped in a piece of insulating cloth—presspahn or leatheroid—at the parts to be embedded in the slots, previous to being pushed into place. The coils, after being secured with

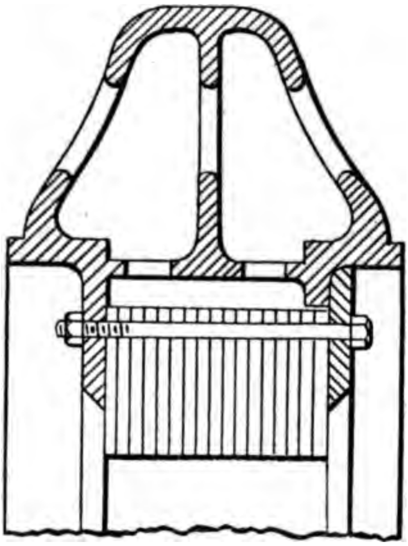

FIG. 197.

[redacted]

wooden wedges driven into the notches at the ends of the teeth, are connected together, and to the terminals of the machine.

The end connections of the coils, projecting some distance from the stator core on either side, are usually protected from mechanical injury by a cast-iron shield, which is closely perforated, so as not to interfere to any extent with the ventilation of the winding. In some instances this is cast in one with the stator case, as shown in Figs. 195 and 196, while in others it is cast separately and bolted on, as in Figs. 189 to 191.

In place of the revolving commutator in the direct-current machine we have, with alternators, two insulated rings connected to the ends of the field winding. As the pressure in this circuit is usually small (100 or 200 volts), no great difficulty is involved in the insulating of the parts. Brushes, attached to ordinary brush-holders, make contact with the rings, and to facilitate trimming while the machine is running, these are usually made in sets of two or more to each ring. Carbon brushes are used in some cases, though the advantages attending the use of carbon brushes in the case of direct-current machines are not necessary in connection with alternators. With carbon brushes, however, standard brush-holders can be employed for all types.

The rings are usually made of cast steel, but sometimes of brass or gun-metal. There is no advantage in using the latter, for the sectional area necessary from mechanical considerations makes the former more than ample for carrying the current. The brush-holders are carried, in some cases, by a separate, overhanging bracket arm, as in Fig. 198, and sometimes by insulated vertical rods, one on either side, supported by a bracket attached to the bearing pedestal, as in Fig. 199; the former being more common in the larger sizes, and the latter in smaller sizes. The connection to the field winding is sometimes made with a copper strip, clamped to one of the fly-wheel spokes, and attached to the inside face of the insulated rings by bolts and washers. This is clearly seen in Figs. 189–191.

We may now consider a few other types, for though the one just described is used far more than any other, not only in this country, but in America, and on the Continent also, still, several other types are in use to a certain extent. In some machines the arrangement of the parts is reversed; the field-magnet system is supported on a yoke ring with the poles directed radially inwards, while the armature core and coils rotate. Machines so made are very similar in construction to the multipolar, direct-current dynamos described in Chapter X., though, with a given diameter, more poles are required. The winding is, of course, different; the armature surface being only partially covered in the single-phase machine. The building up of the armature core on the spider or fly-wheel, with ventilating spaces, etc., is practically identical with that described on p. 172, and therefore need not be further explained. The fixing of the field cores is also carried out in a similar manner. Two slip rings on the shaft are required, to lead the alternating current into and out of the armature winding; and for high tension work this is a distinct disadvantage compared with the revolving field type, in which no break in the armature circuit occurs, except at the switch board. For low pressures, however, with step-up transformers, this type appears to answer fairly well, and is preferred by some engineers.

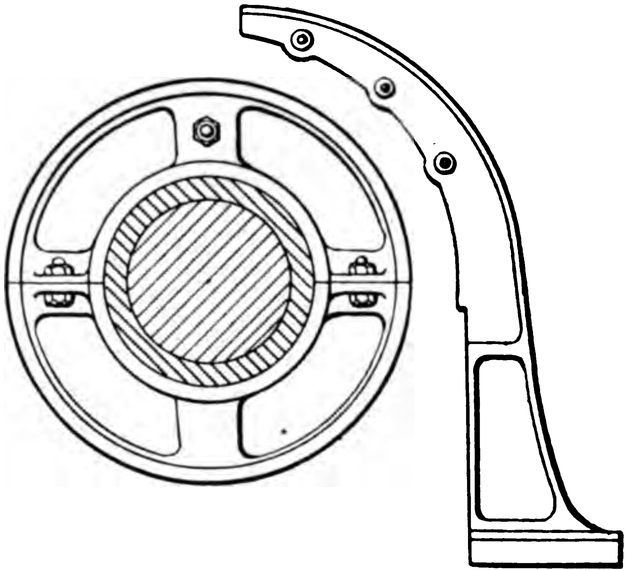

FIG. 198.

Fig. 200 is typical of a number of machines, having only one magnetizing coil for the whole of the field poles, known as monocoil "claw" type revolving field machines. As will be seen from

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the section, the body or rim of the revolving wheel forms the single field core, and is magnetized by one coil of large diameter, marked E.C. The flux is then conducted by means of claw-shaped pole pieces, provided with laminated pole tips, to the armature core, completing its circuit by crossing through it from the one pole piece to the other. All the claw-shaped pole pieces are of similar polarity on the same side, and the claws on either side are interleaved so as to give alternate N. and S. poles all round. The armature core plates are built up in a cast-iron containing case in the ordinary way, and in some instances the winding is threaded through holes instead of being former wound in slots, though this, of course, is not necessarily a feature of this particular type of machine.

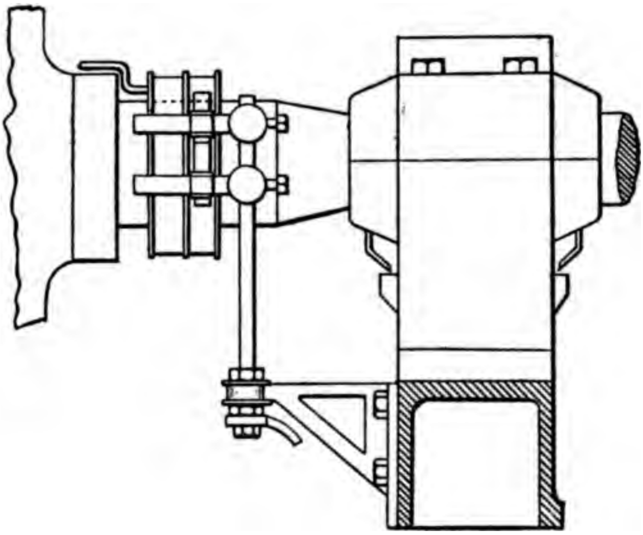

FIG. 199.

The great advantages with this type are the saving in the weight of copper and the energy required for the exciting circuit, and the simplification of the rotating part. The inherent regulation, however, is inferior, especially on inductive loads, for the exciting coil is not in the best position for doing its work effectively. It is almost equivalent to providing a single magnetizing coil over the yoke in the bipolar, direct-current machine, instead of one on each limb. As the load comes on, the field tends to be swept aside considerably more than where a separate coil is provided on each pole, owing to the exciting magnetomotive force being so far removed from the air gaps. This, as explained on p. 244, is more marked the lower the power factor, so that with even small changes in this respect, the pressure varies considerably. Apart from this, it is mechanically superior, and its efficiency is at least as high as in the multiple exciting coil machines.

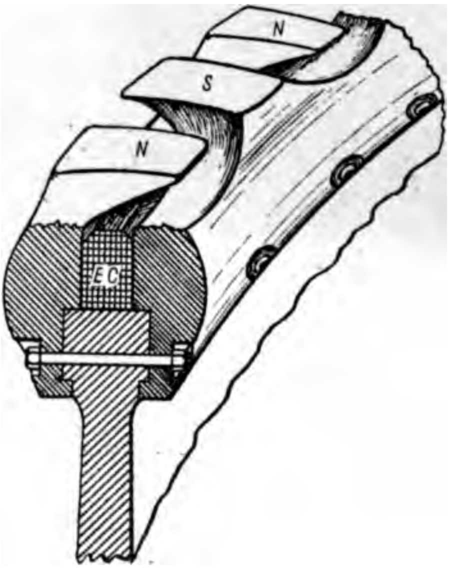

FIG. 200.

Another distinct type, possessing several variations, known as inductor alternators, is shown in Fig. 201. In this case a single magnetizing coil is employed, but neither this, nor the armature coils revolve; both being supported in a stator frame. The only revolving part is the fly-wheel carrying the field-pole pieces, which are magnetized in exactly the same manner as in the last machine considered, for apart from mechanical considerations there is no necessity for the field coil to revolve. In this instance, therefore, we have no moving conductors whatever, and this forms its chief advantage. Against this we have the great disadvantage that only half the armature conductors are effective in building up the electromotive force. For any given pressure, either the number of armature conductors must be doubled, which increases its cost and affects considerably its inherent regulation, or the total flux must be doubled, which increases the size and weight of the iron portion. For this reason the density in the field cores, with this type, is usually very high, and, in order to keep the exciting ampere turns reasonably low, the air gaps are but a mere mechanical clearance in most cases.

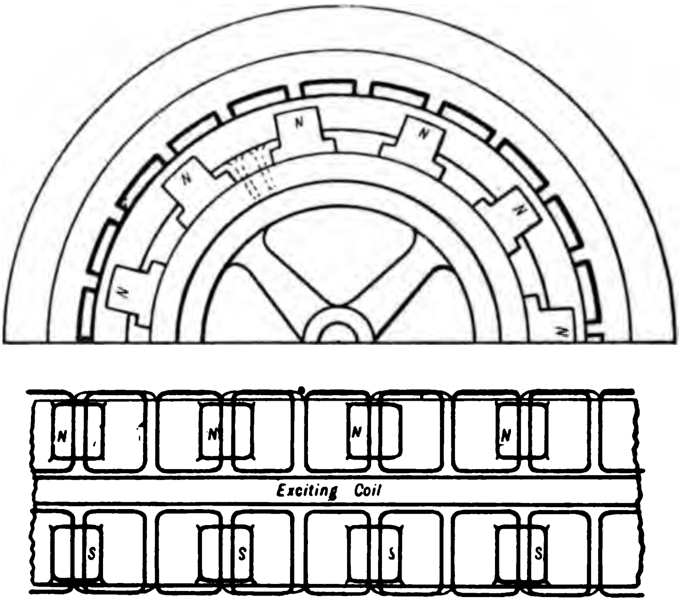

FIG. 201.

It will be noticed that, with the double armature winding, owing to the poles on either side being all of the same polarity, only one side of each coil can be cut by the flux at a time. As the poles move forward, and the lines of force cut the other side of the coils, the electromotive force will be reversed. The two sets can be connected either in series or parallel, as desired.

In another variation of this type only one set of armature coils

[redacted]

is employed, as in the Mordey single inductor alternator, a section of the magnetic circuit of which is given in Fig. 202; and in this case also only one side of each coil is operative at any one time.

In some cases one armature winding is employed, but both air gaps are utilized by staggering the poles, as shown diagrammatically in Fig. 203. Again less than half of each coil can be used, so the result, as regards copper required, is the same, except a little saving in end connections over the double-armature machine

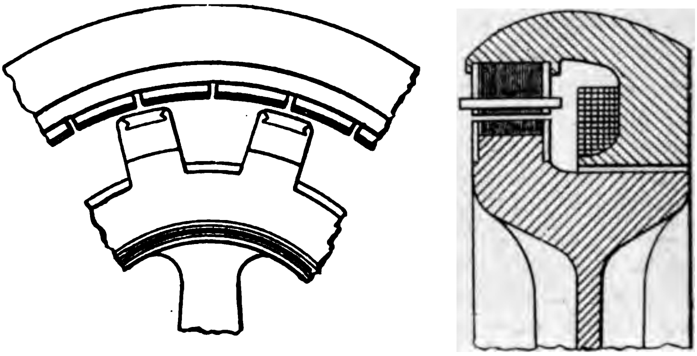

FIG. 202.

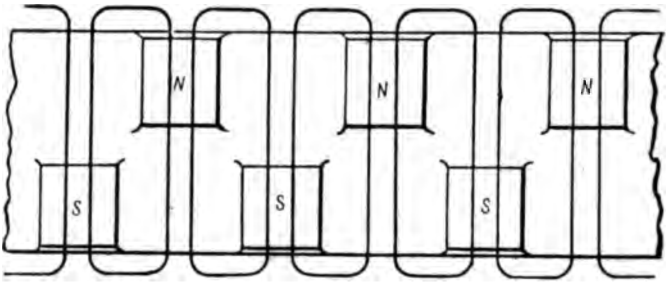

FIG. 203.

In these machines the flux in the armature core never reverses, but first rises to a maximum value and then dies down to zero, rising again to a maximum, and so on, as each pole passes any given section. The flux density may therefore be made considerably higher than is possible with alternate N. and S. pole machines, and the core loss for any given density and periodicity will be considerably less.

The alternators described up to this point are all of the iron-core type with slotted cores, having a fairly large inductance in their circuits. As already mentioned, quite a distinct class exists, sometimes spoken of as the "copper" type, in which the armature circuit contains no iron whatever. In most of these machines the armature winding consists of coils wound with bare copper strip, with fibre or other insulating material between so as to form flat discs, which rotate in a narrow air gap between two crowns of field poles facing each other. Notable machines of this class are the Ferranti, Mordey, and Crompton.

In the Ferranti machine the armature coils are wound separately on fan-shaped cores, made of laminated brass, the narrow ends being cast into solid blocks of brass, whereby two completed coils may be fixed in a special brass frame in pairs; the coil frames forming the connection between the inside ends of the coils. These frames, which are carried by a couple of steel bolts, insulated with corrugated ebonite tubes, are fixed to, but insulated from, the rim of a large fly-wheel. Holes are cored through the rim from side to side, and in these, cast-iron nuts are placed, so that the steel bolts may be screwed into them through holes in the top face of the wheel. These nuts have to be insulated from the fly-wheel, as they are connected through the frames to the armature coils, and for this purpose they are made about $\frac{3}{4}$ inch smaller all round than the hole in which they are placed. After being supported centrally, a composition, consisting chiefly of molten sulphur, is poured in to fill up the intervening space, which, on setting, takes a firm grip of the nut, and also effectively insulates it from the rim. Each coil frame is supported by two bolts and nuts fixed side by side in the above manner. The coil frames are so spaced that the coils pack quite tightly all round, after a strip of vulcanized fibre has been inserted between them to insulate one from the other. The holes in the fly-wheel rim containing the nuts and sulphur are covered by steel plates on both sides.

For high pressures, like 10,000 volts, all the coils are connected in series; but as this would bring the ends at the highest potential difference close together, there would be a great tendency for sparking to occur between the first and last coil. To prevent this, the winding is divided into two parts across a diameter, and a couple of dummy bobbins of hard wood soaked in paraffin wax inserted between them on both sides. The end of the winding on one side then crosses over to the beginning of that on the opposite side, and in this way the potential difference between any two adjacent coils is kept to that generated by two coils only (see Fig. 204).

The field-magnet system consists of a double crown of poles fixed into massive yoke rings, from which they project at right angles to the plane of the ring. These are usually made in four parts, and are machined and bolted together to form the complete ring. There are as many poles in each ring as there are armature coils, and they are wound so as to give alternately N. and S. polarity, and are arranged at a certain distance apart with N. and S. poles facing. Each ring is separately supported by a couple of brackets cast on its lower half, and arrangements are made, by means of right and left handed screws, to draw the two apart to expose the armature coils when necessary. Distance pieces are provided so that, when screwed home, the required width of air gap between the pole pieces is maintained.

To keep the magnetic reluctance and leakage as small as possible, the air-gap length is made no longer than necessary, and to prevent sparking between the rotating coils and the field cores—parts of which are at a potential difference of 10,000 volts—micanite caps, which have a high disruptive strength, are placed over the pole shoes. The coils, rotating at a high peripheral speed, may at times get slightly out of line, and with so small a clearance, very little want of centring would be fatal. It is advisable therefore to open the machine and test it daily. To assist in keeping the coils in line, and to prevent the convolutions from riding over each other, the copper strip employed has a deep corrugation at its centre, and the insulating strip of fibre is pressed to exactly the same shape. In this way the different turns of the coil are more or less locked together. The outer opening between the two yoke rings, through which the armature coils are exposed, is usually covered by a strip of stout sheet steel, to prevent the possibility of anything dropping on to them.

It is the usual practice with these machines to *earth* one end of the winding by bolting it direct to the fly-wheel, the framework of the machine being then connected to earth plates in the station

[redacted]

and to the water main, so that this end of the winding and the framework of the machine must always be at zero potential. Only one collector ring and set of brush gear is then necessary, and attention need be given to the insulation of one main only. It should be noticed, however, that with both mains insulated the maximum potential difference between any part of the winding and the framework is only half that of the machine, and should a fault spring up on one main, it may not lead to a complete breakdown, for a short circuit could not occur unless there were a breakdown on both mains. The arrangement of the parts in these machines will be seen by an inspection of the 650 kw. 10,000 volt machines shown in Figs. 204 and 205. These run at 250 revolutions per minute, and have 20 pairs of poles in each ring, giving a frequency of 83 cycles per second.

It may be noted in passing that, in direct current work, it is found exceedingly difficult to maintain the insulation on the negative pole of the system, for in ordinary working it slowly falls, leading to a rise of potential on the positive main, which may cause a breakdown if it be insulated from earth to withstand only half instead of the full potential difference of the machine.

Messrs. Crompton & Co. have made several machines of similar type, though smaller in size. In these machines the coils are supported in a different manner. The core is made of hard wood instead of laminated brass, and is fitted into a brass block at the inside end, one end of the winding of each coil being attached to the brass block as in the Ferranti machines. The bracket or frame which supports the coil is made of gun-metal, and is firmly bolted to the coil, though insulated from it by plates of fibre on the inside surfaces, and by fibre washers under the bolt head and nut. This bolt is then used to clamp a connection from the inside of one coil to the inside of the next. The gun-metal frame rides on the edge of a cast-iron disc keyed to the shaft, to which it is firmly fixed by bolts, without insulation of any kind. The coils are further supported at the outer edge by insulating clamps of fibre, and a strip of insulating material round the outside of each coil allows of them being packed tightly together. The arrangement of the armature coils is shown in Fig. 206.

Turbine-driven alternators have to be modified considerably owing to the high speeds employed. For any ordinary frequency the number of pairs of poles is seldom greater than two, and for

[redacted]

the smaller sizes, one. The fixing of the revolving field poles and coils is a point requiring most careful consideration and highest class workmanship, as will be understood when it is remembered that they are relatively very large and heavy. With a 3000 kw. machine running at 1000 revolutions per minute the weight of the revolving field magnet complete is over 35 tons, and it revolves at a peripheral speed considerably more than 3 miles per minute. Few of the methods already described for fixing the cores are sufficiently good for this work. In some instances laminated plates with the projecting poles all in one piece are threaded on the shaft and keyed in position, the core being thus laminated throughout. In another case, forgings of steel about 3 inches thick are built up to the required sectional area ; while in other cases the field is solid throughout, or with the limbs bolted or keyed to a solid core. In some Continental

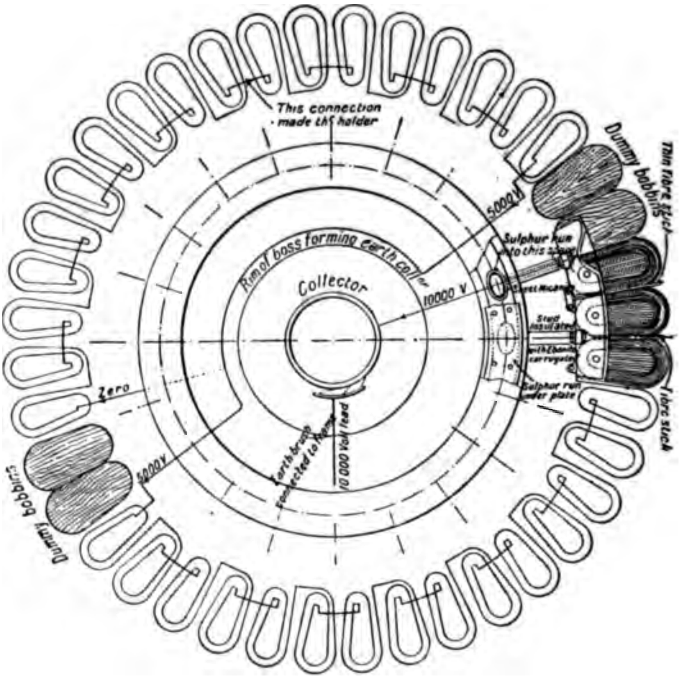

FIG. 204.

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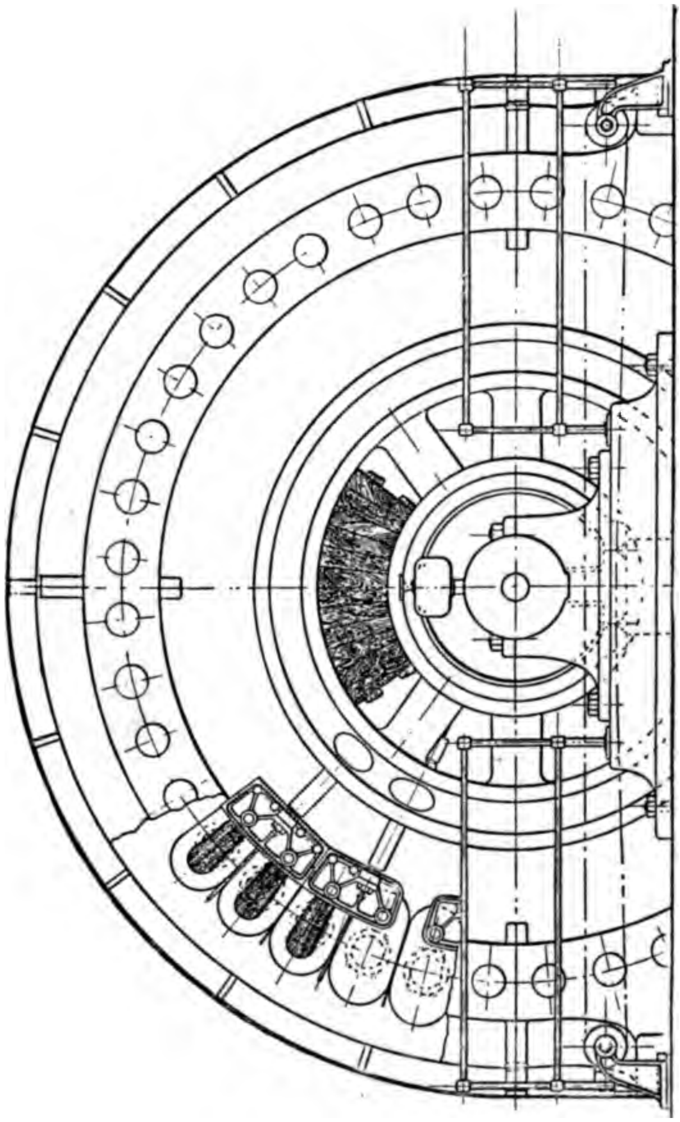

FIG. 205.

turbine alternators the field-magnet system consists of a slotted core, similar to an ordinary bi-polar direct-current armature core,

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the winding being fixed in the slots with wooden wedges. This is connected up so as to produce two or four poles, as desired.

The tendency for the turns of the field winding to slip or ride one over another is very great, owing to the high centrifugal force. Copper strip is therefore used extensively for this work. In the large 5500 kw. turbo-alternators made by the Westinghouse Company, the field is made in a single forging of Whitworth steel, and the sides of the poles are milled out to take the winding and to form ventilating ducts. The winding is then held in these grooves by binding strips driven into notches (see Fig. 207). In some machines made by the Oerlikon Company flat strip winding on edge is employed, and is kept from bulging on the inside by brass clamps, as seen in Fig. 208, which also shows another method of supporting the field cores.

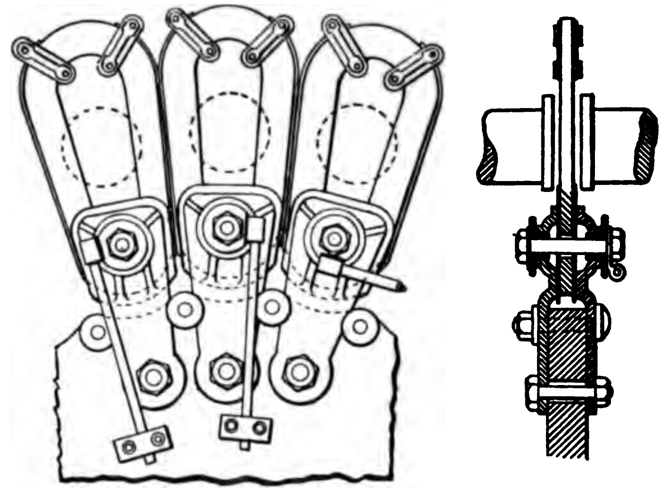

FIG. 206.

For a given output the core losses in a turbo alternator are smaller than in a slow-speed machine, owing to the much smaller size of the core, but, having a much smaller radiating surface, it is more difficult to keep down the temperature. This difficulty is increased by the fact that, owing to the loss of energy and the noise made by churning the air at such high velocity, the moving part has frequently to be surrounded by a continuous metal

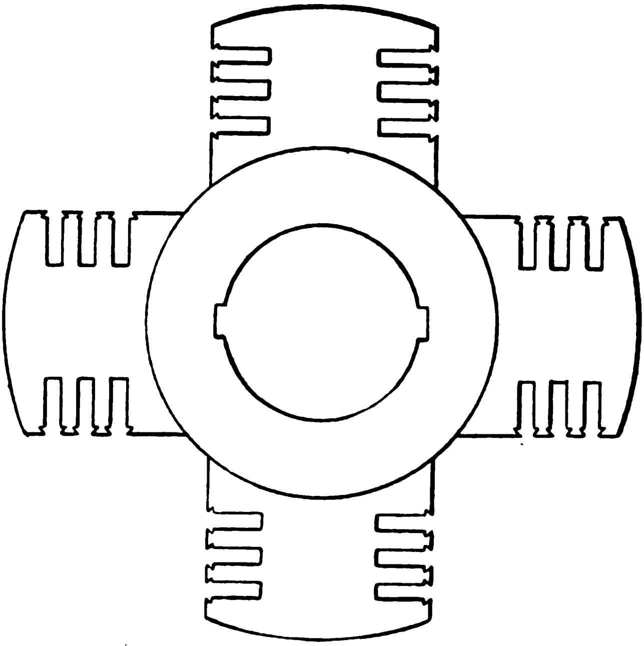

FIG. 207.

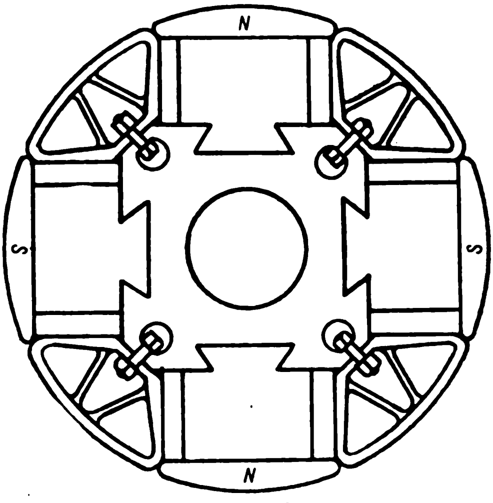

FIG. 208.

covering. In this case a ring, built up of laminations of iron and brass, surrounds the whole, the iron forming the pole pieces, which are riveted to the brass segments and keyed to the field poles, thus presenting a perfectly smooth outer surface. The noise, which is often very great, is minimized by breaking up the free-air path through the machine and providing a more twisted, tortuous one, which again tells against good ventilation.

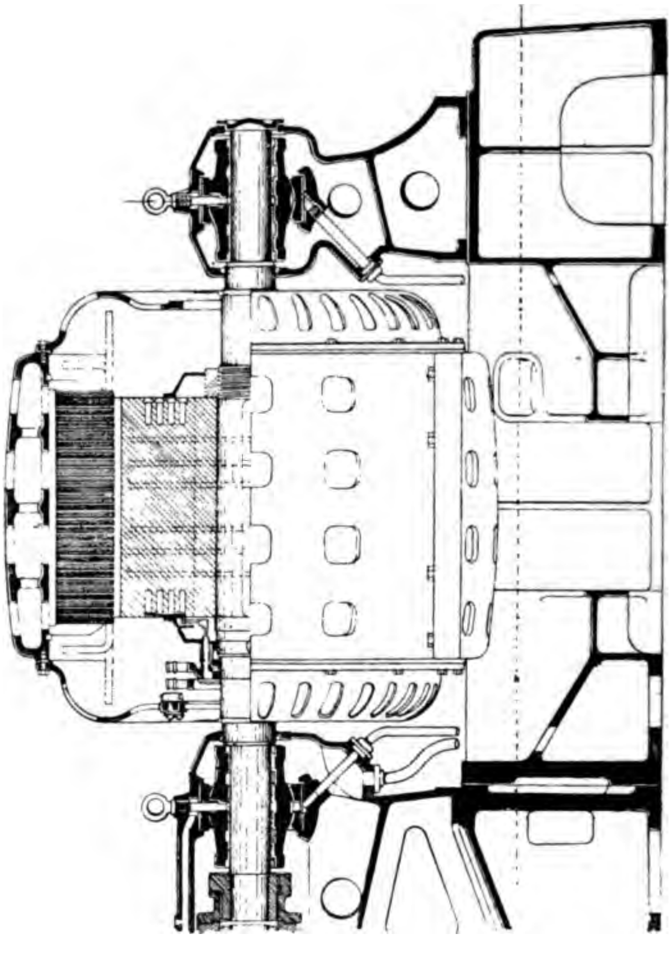

Fig. 209.

[redacted]

On this account it is sometimes found advisable to entirely enclose the machine, and provide forced ventilation by means of blowers. This, however, absorbs considerably more power for the same temperature rise than occurs with the churning of the air in natural ventilation, though the noise is very considerably reduced.

The slightest want of balance in the revolving field will set up

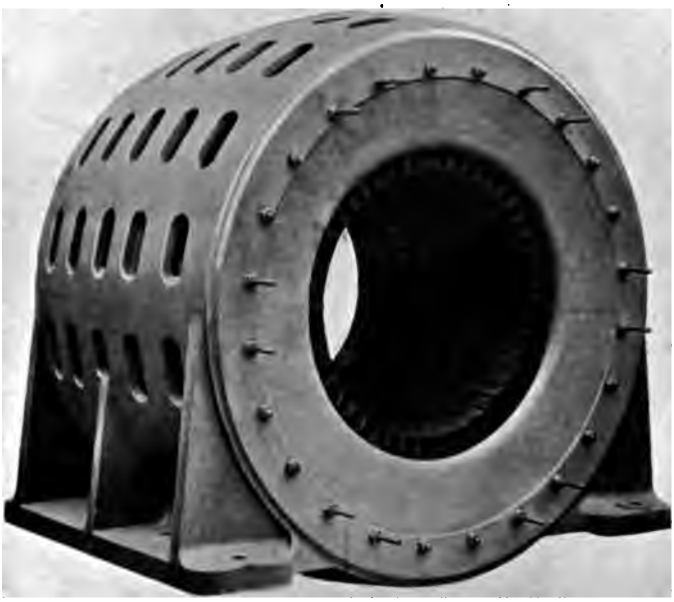

FIG. 210.

vibrations which, at such velocities, soon prove fatal. For this reason special care has to be taken with the winding, etc., so that there shall be no possibility of the slightest shifting. To ensure the iron core being truly balanced, it should be obtained as homogeneous as possible in the first place, and machined all over with the greatest accuracy. It is also of the utmost importance with these high speeds that the machine should run either above or below its critical speed, and preferably the latter, for then the

[redacted]

critical speed is never reached, whereas with the former it passes through it each time in running up and slowing down (see p. 105).

The stator core in such machines is built up in a similar manner to that for large slow-speed machines, and no special difficulties are experienced. Being relatively small in diameter, a stiff outer case is easily obtained, and the only precaution is to provide a maximum cooling surface. The diameter having to be kept as small as possible, the ratio of axial length to diameter is relatively very great compared with ordinary multipolar alternators. The inverted box, or double wall case, owing to its stiffness, is usually employed, with cast-iron protecting hoods for the armature winding, but both case and hoods are cast with a large number of ventilating holes, except in the forced ventilation design. The arrangement of a British Westinghouse machine, half in section, is shown in Fig. 209, and an unwound stator, for a 1600 kw. machine, as made by Messrs. Dick, Kerr, & Co, in Fig. 210.

[redacted]

CHAPTER XIV

POLYPHASE ALTERNATORS

CONSIDER any of the diagrams of single-phase machines shown in Figs. 164 to 172. The core in each case is only half covered, and therefore space remains for a second winding. Suppose we wind the vacant space with an exactly similar winding to that already on. It is evident that we shall obtain a second electromotive force equal to the first, but having its maximum value at a time when the electromotive force in the first has dropped to zero. These windings might be put in series, but in that case we should not get double the output, for the two electromotive forces are differing in phase by 90°, and therefore at times the two are in opposition. The resultant electromotive force of the two will be that of one multiplied by $\sqrt{2}$, or only 1·41 times what it is with the single winding.

We might, however, keep the two windings quite distinct, connected to independent sets of terminals, in which case we may take two separate currents at the same electromotive force, but differing in phase by 90°. This is shown in the curves (Fig. 211), and the machine so wound is called a "two-phase alternator" or "di-phase" machine. If the armature core contains six slots per pole, then each phase would occupy three slots per pole, as represented in Fig. 212. In this case four mains will run from the generator to the switch-board. In fact, we have the equivalent of two alternators in one, and all that has been said in respect to the single-phase generator will apply also to each phase of the di-phase machine.

For transmission purposes the four wires may be reduced to three by combining one wire of each phase. This main then carries the resultant current, which is $\sqrt{2}$ times greater than the current in the other mains, and therefore if we make this main $\sqrt{2}$ times greater in sectional area, so as to keep the current density the same in all, we have a saving in copper in proportion of 3·41 to 4. It must be remembered, however, that the pressure between this common wire and either of the others is now $\sqrt{2}$ times greater than it would be if four wires were used throughout, and therefore better insulation is required.

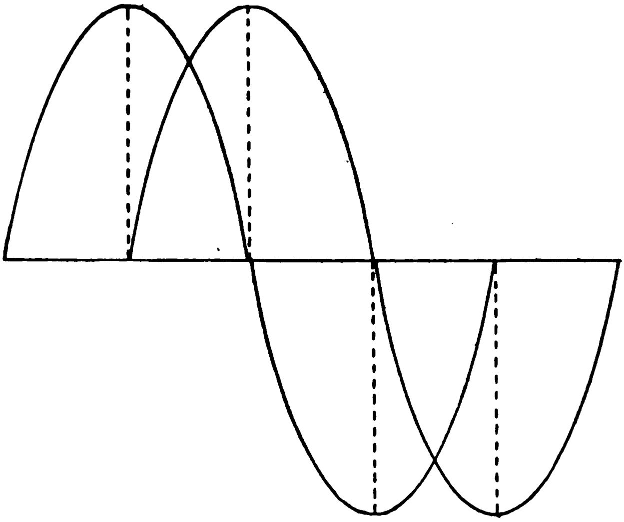

FIG. 211.

If the winding space be divided up into three equal parts, and three separate coils per pole be wound in the slots instead of two,

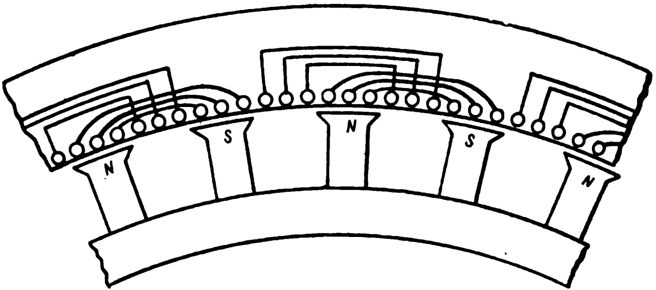

FIG. 212.

we shall get three electromotive forces differing in phase by 60°, and the ends of each winding being brought out to separate terminals, we have six ends which may be connected up in different ways or used as three separate independent circuits. The usual practice is to reverse the middle windings relatively to the other two and connect them together, so as to obtain three electromotive forces differing by 120°, as shown in the vector diagram (Fig. 213), where OA, OB, OC represent the three electromotive forces, and OB_1 the one phase reversed.

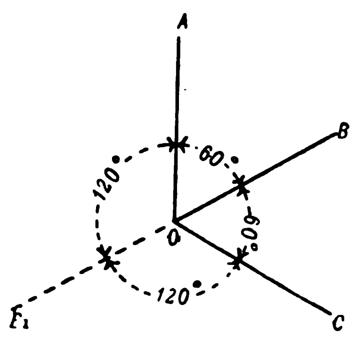

FIG. 213.

These windings are usually connected together in "star" or "mesh" connection, the former being represented diagrammatically in Fig. 214 and the latter in Fig. 215. In either case only three terminals are provided, and only three-line wires are required. It should be noticed that with the star connection the electromotive force across the line wires is greater than that in the armature windings, for that between any two wires is the resultant of the electromotive force generated by two phases, and

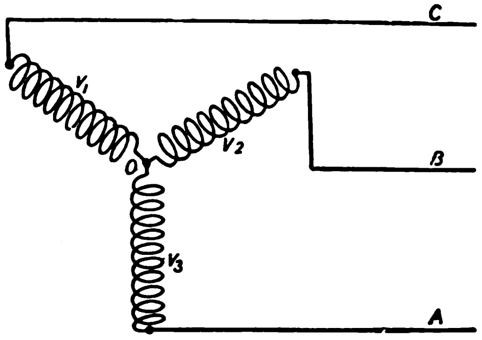

FIG. 214.

the resultant of two equal forces differing by 120° is $\sqrt{3}$ times that of one. The armature winding and line wires being in series, the current in them is the same and in the same phase. With mesh connection the electromotive force between the line wires is the same as that on each of the armature windings, but each line is fed by current from two phases, and is therefore $\sqrt{3}$ times greater than the armature current.

With mesh connection the armature winding is closed on itself, or short-circuited, yet no current flows round, for the resultant electromotive force is nought at every instant, as will be seen by considering the three-phase curves of electromotive force in Fig. 216, where the sum of the two in one direction is equal to the third in the opposite direction at every point.

If an ammeter be put into one of the line wires to measure the current, and a voltmeter connected across two of them to indicate the pressure per phase, the power per phase obtained by taking the product of the two and multiplying by the power factor would be $\sqrt{3}$ times too great, whether connected in star or mesh, for in one case the pressure, and in the other the current, is $\sqrt{3}$ times greater than that developed in the armature winding per phase. The power per phase would therefore be obtained by dividing the above product by $\sqrt{3}$, or power per phase $= \dfrac{\mathrm{I} \times \mathrm{E} \times \cos\theta}{\sqrt{3}}$, and the total power delivered by the three phases $= \dfrac{\mathrm{I} \times \mathrm{E} \times \cos\theta}{\sqrt{3}} \times 3 = \mathrm{I} \times \mathrm{E} \times \cos\theta \times \sqrt{3}$.

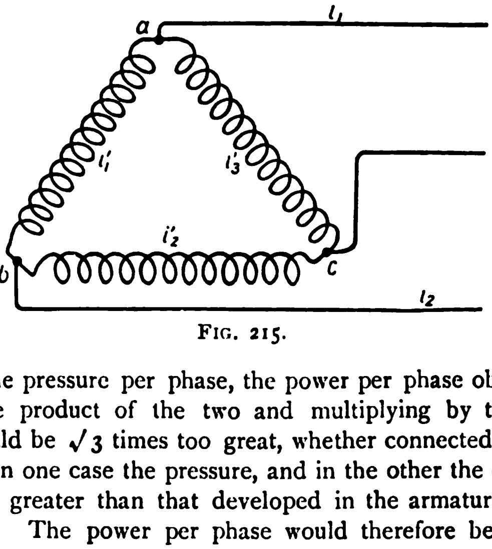

FIG. 215.

With the armature coils connected in "star" there is a saving in copper for the line wires, in comparison with the three separate circuits using six wires, of 3 : 6 or 50 per cent., while with mesh connection the saving is only $3 \times \sqrt{3} : 6$ or 13 per cent., and therefore there is a saving of copper for the line wires in star as compared with mesh connections of 3 : 5·19 or 42 per cent.

It is seldom that more than six slots per pole are employed for the armature winding. In fact, this figure has become almost a standard practice, though we find special cases where eight, nine, and even more are employed. With six slots per pole, the same core plates serve for either single-, two-, or three-phase machines. With single phase, two or three slots per pole would be wound, and the remainder left vacant. With three-phase, all the slots would be utilized, giving two slots per pole per phase. The shape of the slots varies somewhat, as in direct-current machines, but the most common is the rectangular open type, which allows of former-wound coils, and these are usually fixed by wooden wedges driven into notches in the ends of the teeth, as shown in Figs. 217 and 218.

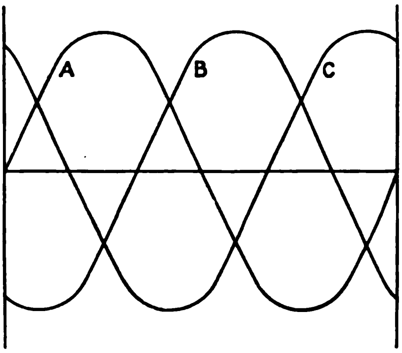

FIG. 216.

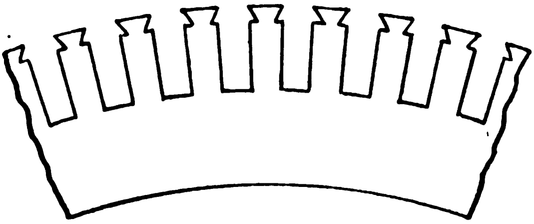

FIG. 217.

With three-phase machines there is considerable overlapping at the ends of the coils with *ordinary* winding, so that the three phases have to be bent to lie on three different planes. For this reason *hemitropic* winding is more commonly employed, as represented in Fig. 219, in which case the three phases can be made to lie in two planes, by arranging one set of coils with straight ends, and bending the other two sets in the same plane so as to pass over the first.

With two-phase machines, either ordinary or hemitropic

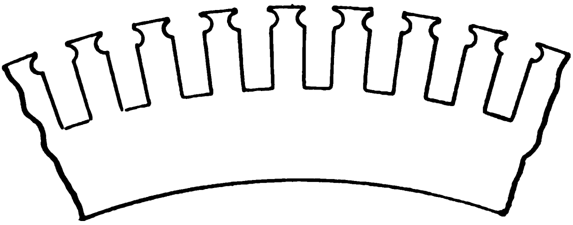

FIG. 218.

winding can be employed. One phase is bent up so as to lie flat against the end plates of the armature core, and the other phase left straight ended. Fig. 220 shows one phase of a two-phase, six-pole, coil-wound armature, with two slots per pole per phase, and Fig. 221 a three-phase, eight-pole, bar-wound armature, with four bars per pole per phase.

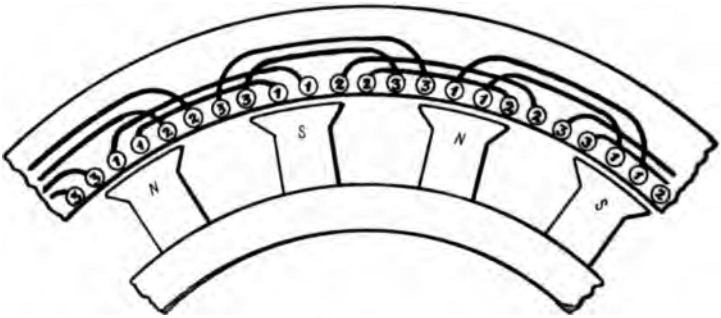

FIG. 219.

In calculating the characteristic of a three-phase alternator, the separate phases can be treated independently. The interaction of the phases often has the effect of changing the position of the coil where the maximum inductance occurs, but it has little effect on the average value of any one phase.

The resultant armature magnetomotive force due to the three phases is equal to twice that of one phase. This will be seen at once when it is remembered that the phases are 60° apart, and are only made 120° apart by reversing the intermediate phase. Fig. 222 shows three vectors, 60° apart, the line OD being the resultant of the three.

For a given maximum armature strength we can put on 50 per cent. more ampere turns per pole with three-phase machines than with single phase, but this is seldom or never done, owing to the unbalancing of voltage that would result if the phases were not all similarly loaded. This gives the three-phase machine a better excitation characteristic than the corresponding single-phase machine.

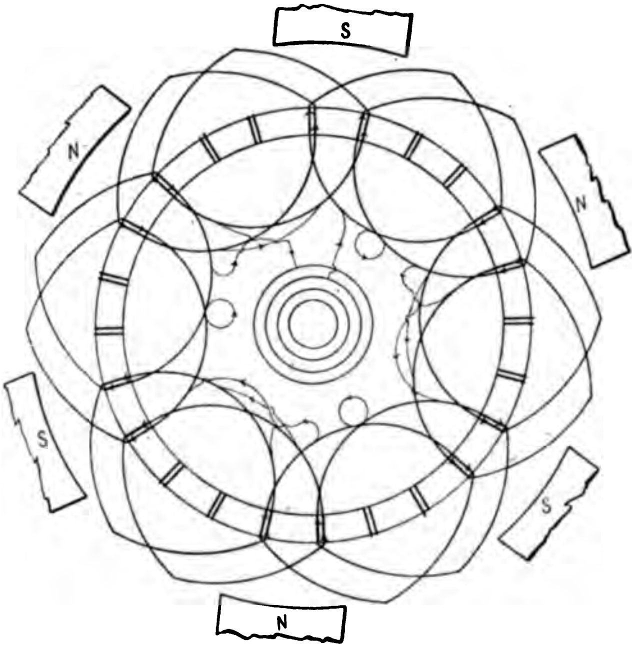

FIG. 220.

One great advantage in polyphase generators over single phase is in the better utilization of the armature core, making the

[redacted]

machine for a given output considerably cheaper to build, and lighter in weight.

In designing alternators, several points differing from direct-current design have to be considered, though, in the main, we proceed on similar lines. The design of the field-magnet system and the no-load excitation are practically the same, and there is no trouble about commutating difficulties, though we have, instead, to consider the means of obtaining the best possible inherent regulation with high efficiency.

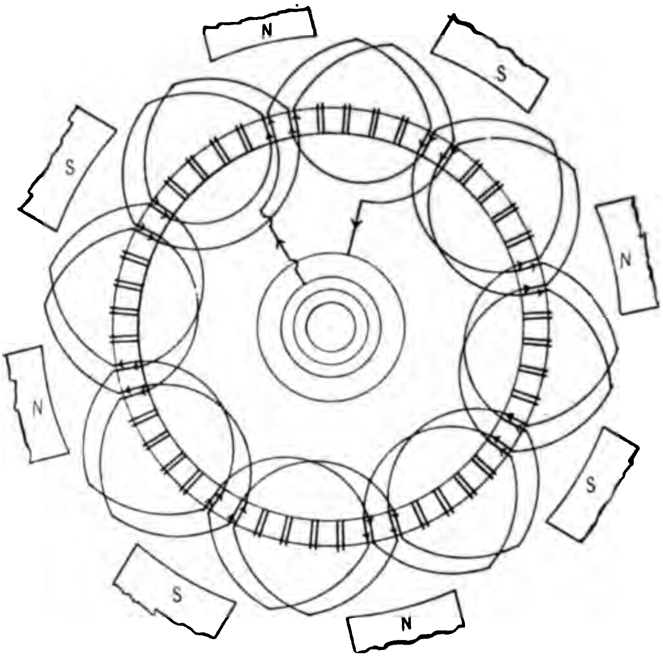

FIG. 221.

With any given capacity, frequency, and voltage, either of the types described may be employed, though the ironless-cored, disc-type machines are never made for any but single phase. The separate phases of a polyphase machine are treated as a single-phase machine of the same output with the appropriate constants. There is one marked difference, however, in the three-phase, when compared with the single-phase machine, namely, the ratio of pole arc to pole pitch. With single-phase machines this does not exceed 50 per cent., owing to the differential action brought about by a higher ratio, but with three-phase machines only one-third of the pole pitch is occupied by the winding of any one phase, and therefore the ratio can be increased to 66 per cent. without differential action.

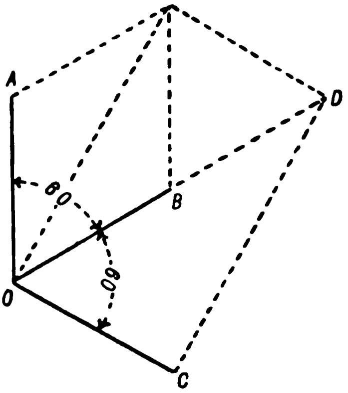

FIG. 222.

By way of illustration, let us consider a 1000 kw. three-phase machine for 5000 volts between the terminals, 50 cycles, 120 revolutions per minute. Being star-connected, the volts generated in each of the armature phases will be $= \frac{5000}{\sqrt{3}} = 2886$ volts, and the kw. per phase $= \frac{1000}{3} = 333\cdot\dot{3}$, and therefore the current per phase $\frac{333333}{2886} = 115$ amperes.

As we have already seen, the most commonly employed type at the present time, for both single and polyphase machines, is the revolving field, iron-cored slotted armature type, the maximum peripheral speed of which varies from 4000 to 6000 feet per minute. In such machines the pole pitch will be found to be close to 10 inches in practically all sizes, the maximum range of differences lying between 8 inches and 12 inches. This decides the diameter of the armature, for we must have a certain number of poles to give the required frequency at the required speed.

With the inductor type of alternator, owing to the absence of wound coils on each pole, a higher peripheral speed is permissible. This sometimes runs up to 7000 feet per minute.

The frequency will be = revolutions per second × pairs of poles, and therefore the number of *pairs* of poles $= \frac{\text{frequency}}{\text{revs. per second}}$, which in our case $= \frac{50}{2} = 25$, or total number of poles $= 50$. With a pole pitch of 10 inches, we get the circumference

[redacted]

of the armature bore = 500 inches, and the diameter = $\frac{500}{\pi}$ = 159 inches. This gives a peripheral speed of $\frac{500}{12} \times 120 = 5000$ feet per minute.

The axial length of the armature may now be determined from a formula very similar to that given on p. 188, in connection with multipolar direct-current machines, viz.—

$$\left.\begin{matrix}\text{total watts or volt-amperes per phase}\\ \times \text{ number of phases}\end{matrix}\right\} = KD^2LS,$$

where the symbols have the same meaning, and where the values of K, for a frequency of about 50, are—

	Values of K.
For single phase, up to about 30 kw.	0·0083
„ „ from 30 to about 60 kw.	0·01
„ „ „ 60 „ 100 „	0·0111
„ „ „ 100 „ 300 „	0·0124
„ „ „ 300 to largest sizes	0·0166
For polyphase (either 2 or 3 phase), up to 30 kw. . .	0·0111
„ „ from 30 to about 60 kw.	0·0143
„ „ „ 60 „ 100 „	0·0166
„ „ „ 100 „ 300 „	0·018
„ „ „ 300 to largest sizes	0·02

These values vary with the frequency, being slightly higher with a higher frequency. With inductor alternators the values are slightly less.

Putting in the appropriate values in our case, we get—

$$\text{length of armature} = \frac{1{,}000{,}000}{159^2 \times 120 \times 0{\cdot}02} = 16 \text{ inches}$$

It has been pointed out that it is now becoming the usual practice to employ six slots per pole per phase with open parallel sides, whether for single-, two-, or three-phase machines. Of course, in special cases we find quite a different number; for instance, in single-phase machines, it is not at all uncommon to find, especially with high voltages, a single slot per pole, though these are noisy in running, and their inherent regulation is, as a rule, inferior. In three-phase machines as many as five slots per pole per phase, or fifteen slots per pole, have been employed. The slots are in many cases partially closed, but it is rarely that completely closed slots are employed on account of magnetic leakage, and the large inductive drop caused thereby. Owing to

[redacted]

the large inductance of coils in deep slots, the depth seldom exceeds three times the width; twice the width being preferable where possible.

With stationary armatures and revolving fields, there is not the same cooling action in the armature core and winding, for the fanning action due to rotation is absent. For this reason it is advisable to employ a smaller current density. A maximum of 1500 to 1800 amperes per square inch is a common allowance.

For good regulation the armature strength in ampere bars per inch of surface should not exceed 300, or, at the outside, 350. This again is similar to the rule given on p. 194 for direct-current machines. With a value of 345 for the armature strength, we get—

$$\text{ampere bars per inch} = 345$$

and the current in amperes being 115, we have—

$$\text{bars or conductors per inch} = \tfrac{345}{115} = 3$$

There being 500 inches in the armature circumference, we have the approximate number of conductors on the armature = 1500. Dividing by 3, we get 500 conductors per phase, and as we have 100 slots per phase, we have 5 conductors per slot.

Taking a current density of 1500 amperes per square inch, we get the sectional area of each conductor $= \tfrac{115}{1500} = 0{\cdot}076$ sq. inch, and therefore the sectional area of copper in the slots $= 0{\cdot}076 \times 5 = 0{\cdot}380$ sq. inch. With a space factor of 0·3, the sectional area of the slots will be $\frac{0{\cdot}3}{0{\cdot}380} = 0{\cdot}8$ sq. inch practically, and with a depth equal to twice the width we get the depth of the slots 1·3 inch and the width 0·6 inch. There being six slots per pole, and the pole pitch being 10 inches, the width of each of the teeth will be 1·06 inch.

The length of the embedded portion of the armature winding *per turn* will be 32 inches, and that of the free portion practically 30 inches, or three times the pole pitch. Total length per turn = 62 inches, and therefore the length of winding per phase $= 62 \times 250 = 15{,}500$ inches.

The resistance per phase, allowing for a temperature rise of 35° C., $= \frac{\text{length}}{\text{sect. area}} \times \text{sp. res.} = \frac{15{,}500}{0{\cdot}076} \times \frac{0{\cdot}75}{10^6} = 0{\cdot}153$ ohm.

The CR drop at full load = 115 × 0·153 = 17·6 volts, and the C^2R loss per phase at full load = $115^2 \times 0{\cdot}153 = 2023$ watts. Total armature C^2R loss at full speed = 6069 watts.

For this size core, four ventilating ducts should be allowed, each about 0·5 inch wide, making the length of laminations = 14 inches, and deducting about 10 per cent. for insulation between the plates, we get the net length of iron in the armature = 12·6 inches.

With alternators, owing to the high frequency of reversals in the armature core, the flux densities are usually lower than in direct-current machines. The flux densities commonly employed for the revolving field alternate-pole type at full load are—

For field cores . .	15,000 to 17,000	lines per sq. cm.
„ yokes . . .	6,000 to 8,000	„ „
„ armature core . .	7,000 to 8,000	„ „
„ armature teeth . .	12,000 to 17,000	„ „
„ air gaps . . .	5,000 to 8,000	„ „

At no load these values should be from 10 per cent. to 15 per cent. less, owing to the additional flux at full load, required for overcoming the reactance back voltage.

The full-load voltage to be generated will be the vectoral sum of the no-load and CR voltage and the reactance voltage.

Applying our formula for the no-load electromotive force given on p. 241, we have—

$$E = \frac{K p N C S}{10^8}$$

therefore—

$$2886 = \frac{2{\cdot}25 \times 25 \times N \times 500 \times 2}{10^8}$$

therefore—

$$N = \frac{2886 \times 10^8}{2{\cdot}25 \times 25 \times 500 \times 2} = 5{,}130{,}600$$

or, the total lines of force at no load entering the armature from any one pole must be = 5,130,600.

Taking the lower values given above, in the case of the yoke and cores, for the no-load density, and allowing a leaking factor of 1·3, we have—

[redacted]

total no-load flux in the field-magnet cores . . . = 6,669,780
density at no load in the field cores . . . . . = 15,000
therefore sectional area of field cores . . . = $\frac{6669780}{15000}$
= 444·6 sq. cms., or 69 sq. inches

The over-all length of the armature laminations is = 16 inches, and if we allow 0·5 inch at each end for fringing, we get the axial length of the field poles = 15 inches, and therefore the breadth of the field cores = 4·6 inches.

The length of the curved surface of the pole shoes will be 66 per cent. of the pole pitch = 6·6 inches.

The no-load density in the armature core will be 7000 lines per square centimetre, and therefore the sectional area of the armature core below the slots will be $\frac{2565300}{7000}$ = 366 sq. cms.

The length of iron in the armature laminations = 32 cms., therefore the radial depth of the armature laminations below the slots = $\frac{366}{32}$ = 11·4 cms. = 4·5 inches.

With a density in the yoke at no load of 6000 lines per square centimetre, the sectional area of the yoke will be $\frac{3334890}{6000}$ = 555·8 sq. cms. = 87·7 sq. inches.

Making the length of yoke rim 1 inch longer than the cores at each side, we have—

$$\text{thickness of yoke ring} = \frac{87 \cdot 7}{16} = 5 \cdot 4 \text{ inches}$$

To approximate to a sine wave, the pole shoes should be well rounded on the surface, and this will give a varying length to the air gap. The narrowest point in the gap should not be less than $\frac{3}{16}$ inch with this size machine, making the average length of the air gap 0·25 inch.

The radial length of the field cores has to be estimated and readjusted afterwards if found to be unsuitable, as in direct-current machines. A radial length about equal to the pole-face length is usually found sufficient, which in our case gives the length of the field cores as 6·6 inches.

The sectional area of the pole faces will be 6·6 × 16 = 105·6 sq. inches = 681 sq. cms. The effective area of the air gap obtained by increasing the pole-face dimensions by 0·8 times the air-gap length all round gives the value 740 sq. cms., and therefore the air-gap density $= \frac{5130600}{740} = 6946$.

Each pole shoe will cover 4 teeth, and the mean sectional area of iron in each tooth will be $1·06 \times 12·6 = 13·356$ sq. inch $= 86$ sq. cms.

The tooth density will therefore be $= \dfrac{5,130,600}{86 \times 4} = 14,900$.

We can now assemble the various lengths, sectional areas, and densities, and calculate the no-load excitation.

	Total flux.	Sect. area in sq. cms.	Density.	Ampere turns per cm.	Length in cms.	Total ampere turns.
Field cores (wrought iron)	6,669,780	444·6	15,000	26	33·5	871
Yoke (cast steel) . .	3,334,890	555·8	6,000	4·5	25	112
Armature core (sheet steel)	5,130,600	366	7,000	5	38	190
Teeth . . .	5,130,600	344	14,900	38	3·05	116
Air gaps . .	5,130,600	650	6,946	$0·8 \times 6946$	1·27	5556

Total ampere turns for the no-load electromotive force per magnetic circuit, or per pair of poles = 6845, therefore ampere turns per pole = 3422.

We may now calculate approximately the inductance of the machine by the method explained on p. 247. The length of the free portion per turn being equal to 30 inches, the lines per ampere turn for the free portion $= 1·25 \times 30 = 37·5$. For the embedded portion we may take a value of 10 for the lines per ampere turn per inch, therefore the lines per ampere turn for the embedded portion $= 10 \times 32 = 320$. The total lines per ampere turn will therefore be $37·5 + 320 = 357·5$.

The average inductance of each coil will be $= \dfrac{357·5 \times 10^2}{10^8}$ $= 0·000357$ henry.

The average inductance of the winding per phase $= 0·000057 \times 25 = 0·009$ henry.

Reactance voltage at full load $= 2\pi n LI = 6·28 \times 50 \times 0·009 \times 115 = 325$ volts.

The total armature ampere turns per phase at full load

$= 115 \times 250 = 28{,}750$, and therefore the ampere turns per pole per phase $= \frac{28750}{50} = 575$, the maximum value of which will be $= 575 \times \sqrt{2} = 793$. The resultant of the three phases will be $= 793 \times 2 = 1586$ ampere turns per pole. This, then, will be the excitation required to send the full-load current of 115 amperes through the short-circuited machine.

The tangent of the angle of lag at full load, with unity power factor in the external circuit, will be $\frac{325}{2903} = 0{\cdot}11$ = tangent of 6·5°.

The sine of 6·5° (the angle of lag) = 0·11.

Demagnetizing ampere turns per pole $= 1586 \times 0{\cdot}11 = 174$, therefore the full-load exciting ampere turns per pole for 2886 volts per phase with unity power factor $= 3422 + 174 = 3596$.

For three-quarter load we have—

Armature ampere turns . . = 21,562.
Ampere turns per pole . . $= \frac{21562}{50} = 431$.
Maximum value of ampere turns per pole . . . . . $= 431 \times \sqrt{2} = 609$.
Resultant of three phases . . $= 609 \times 2 = 1218$ ampere turns per pole
Reactance voltance . . . $= 6{\cdot}28 \times 50 \times 0{\cdot}099 \times 86{\cdot}25$ = 243 volts.
Tangent of angle of lag . . $= \frac{243}{2899} = 0{\cdot}083$ = tan 5°.
Sine of 5° . . . . . . = 0·083.
Demagnetizing ampere turns per pole at $\frac{3}{4}$ load . . . $= 1218 \times 0{\cdot}083 = 101$.
Exciting ampere turns at $\frac{3}{4}$ load, with unity power factor . = 3523.

At half load—

Armature ampere turns . . = 14370.
Armature ampere turns per pole . $= \frac{14370}{50} = 287$.
Maximum ampere turns per pole. $= 287 \times \sqrt{2} = 405$.
Resultant of three phases . . $= 405 \times 2 = 810$.
Reactance voltage . . . $= 6{\cdot}28 \times 50 \times 0{\cdot}009 \times 57$ = 162 volts.
Tangent of angle of lag . . $= \frac{162}{2894} = 0{\cdot}056$.
Sine of angle of lag . . . = 0·056.
Demagnetizing ampere turns per pole at $\frac{1}{2}$ load . . . = 45.
Exciting ampere turns per pole at $\frac{1}{2}$ load . . . . = 3467.

[redacted]

At quarter full load—

Armature ampere turns . . $= 7185$.

Armature ampere turns per pole . $= \frac{7185}{50} = 143$.

Maximum ampere turns per pole . $= 143 \times \sqrt{2} = 202$

Resultant of three phases . . $= 202 \times 2 = 404$.

Reactance voltage . . . $= 6{\cdot}25 \times 50 \times 0{\cdot}009 \times 29$
$= 81$ volts.

Tangent of angle of lag . . $= \frac{81}{2890} = 0{\cdot}028$.

Sine of angle of lag . . . $= 0{\cdot}028$.

Demagnetizing ampere turns at $\frac{1}{4}$ full load . . . . . $= 6$.

Exciting ampere turns per pole at $\frac{1}{4}$ load . . . . . $= 3428$.

From these values the excitation characteristic, with unity power factor in the external circuit, may be plotted, as in

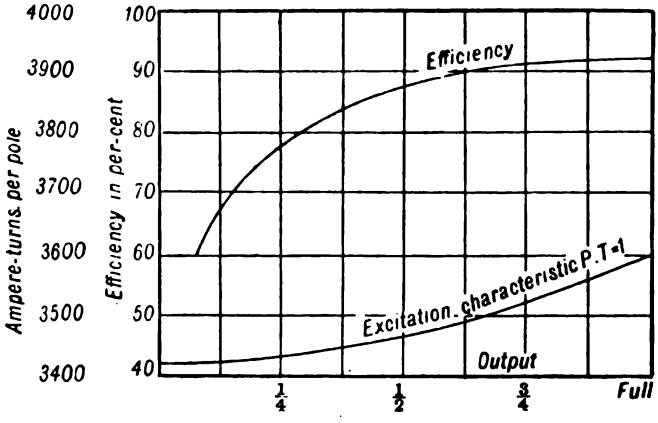

FIG. 223.

Fig. 223. This must necessarily be only approximately correct, owing to the number of constants employed which are only found accurately by experiment.

For a power factor in the external circuit of 0·8, the cosine of the angle of lag = 0·8, and therefore the angle of lag = 36°. The angle of lag in the armature winding found graphically, as explained on p. 248, is 40°. The sine of 40° = 0·64, and therefore the demagnetizing ampere turns per pole at full load for

[redacted]

a power factor in the external circuit of 0·8 = 1586 × 0·64 = 1015.

Full load exciting ampere turns for power factor of 0·8 = 3422 + 1015 = 4437 per pole.

The same can be done for other loads, and a second characteristic curve for a power factor of 0·8 plotted.

Allowing 1 per cent of the machine output for excitation watts, we have—

$$\text{excitation watts} = 10{,}000.$$
$$\text{watts per coil} = \tfrac{10000}{50} = 200.$$

With 200 volts for the exciting circuit, we have, volts per coil = $\frac{200}{50}$ = 4, and therefore exciting current = $\frac{200}{4}$ = 50 amps., and the resistance of each coil 0·08 ohm. The total number of turns per pole = $\frac{4437}{50}$ = 89.

If we wind this in a single layer of flat strip, on edge, the depth of winding will probably not exceed one inch, in which case, the length of winding per pole, allowing for the bobbin and insulation, will be approximately = 4000 inches.

The sectional area of the winding will be—

$$\text{sect. area} = \frac{\text{length} \times \text{sp. resistance}}{\text{resistance}}$$
$$= \frac{4000 \times 0{\cdot}75}{0{\cdot}08 \times 10^6} = 0{\cdot}037 \text{ sq. inch}$$

and therefore the current density = $\dfrac{50}{0{\cdot}037}$ = 1350 amps. per square inch.

The thickness of the copper strip will be = 0·037 inch, and therefore the 89 turns will occupy 3·3 inches of the winding length, which allows an equal thickness of insulating material between each convolution.

Calculating the core loss, as explained on p. 212, we have—

Mean sectional area of iron in the whole of the teeth . . = 86 × 300 = 25,800 sq. cms.
Length of teeth . . . . . = 1·3 ins. = 3·3 cms.
Volume of teeth . . . . . = 85,140 c.cms.
Density in the teeth . . . . = 14,900.
Watts per c.cm per cycle . . = 0·0038.
Cycles per second . . . . = 50.

[redacted]

Total watts lost per cycle . . = 323.
Total watts lost in the teeth . = 16,150.

Cross sect. area of iron in the core = 366 sq. cms.
Mean total length of core . . = 1304 cms.
Volume of iron in core . . = 477,264 c.cms.
Mean density in the core . . = 7000.
Watts per c.cm. per cycle . . = 0·0012.
Total watts per cycle . . . = 572.
Total watts lost in core . . = $572 \times 50 = 28{,}600$.
Total watts lost in core and teeth = 44,750.
Total armature loss . . . = 50,820 watts.

The total amount of cooling surface in the armature core will be the whole superficial area, viz.—

Area of the outer periphery = 31,486 sq. cms.
Area of the inner periphery = 29,210 „ „
Area of the two ends = 29,730 „ „
Total radiating area = 90,426 „ „

Therefore the watts per square centimetre of radiating surface $= \frac{50820}{90426} = 0{\cdot}56$.

For a temperature rise of 35° C., the watts per square centimetre, worked out in this way, will usually be about 0·75 with stationary armatures, and about 1·25 with revolving armatures.

The bearing and air friction loss will be approximately $= 0{\cdot}0003D^2LR$ watts $= 0{\cdot}0003 \times 159^2 \times 16 \times 120 = 14{,}560$ watts.

The approximate commercial efficiency, worked out in a similar manner to that given on p. 215, will therefore be—

at full load, eff. $= \frac{1000000}{1075380} = 93$ per cent.
at $\frac{3}{4}$ load, eff. $= \frac{750000}{820192} = 91$ „
at $\frac{1}{2}$ load, eff. $= \frac{500000}{568430} = 88$ „
at $\frac{1}{4}$ load, eff. $= \frac{250000}{316830} = 78$ „

These values are plotted in the curve (Fig. 223).

[redacted]

CHAPTER XV

EXCITING, COMPOUNDING, AND SYNCHRONIZING OF ALTERNATORS

ALL alternators require a direct-current supply to excite the field magnets, and therefore in most stations where alternators are employed we also find direct-current machinery installed. The power required for the exciting circuit is, however, small compared with the output of the alternator, so that quite a small direct-current machine driven from the alternator shaft suffices in many cases. In large stations, the direct-current machinery often forms a separate exciter plant, composed of larger, and therefore more efficient, units. In a few instances, a fractional part of the alternating current is commuted or rectified into direct current for exciting purposes, though this is more often employed in providing a compounding current in a separate winding, as will be explained later.

With the separate exciting dynamo to each alternator, driven from the shaft, the main units are all self-contained and independent of each other, and the starting up of the main alternator starts up the exciter with it, but it has the disadvantage that the main machine will run, usually, at a relatively low speed, unsuited for driving a small-sized, direct-current machine, so that either the exciter must be geared to the alternator shaft by belt or spur gearing, or the exciter must be built with a large number of poles. The former method is unsatisfactory, for belts or ropes, which have been used largely, are apt to break or slip. In the first event the machine would be left without excitation, and if working in parallel with others, would form a short circuit which may shut down the whole station. The noise of spur-gearing tells seriously against its use. The multipolar exciter, often with six or eight poles, built on an extension of the alternator shaft, seems preferable, and is very largely used.

Where separate exciting plant is installed, as in large power stations, the exciters are connected up to omnibus-bars, so that one may be used singly, or two or more in parallel. Current is then fed from these bus-bars to the various alternator field circuits through rheostats controlled from the main alternator switchboard. In this case it is often the practice to install a battery of accumulators also, which acts as a stand-by in case of complete breakdown in the exciting plant; the throwing over of a switch being sufficient to put the battery on to the exciting bus-bars.

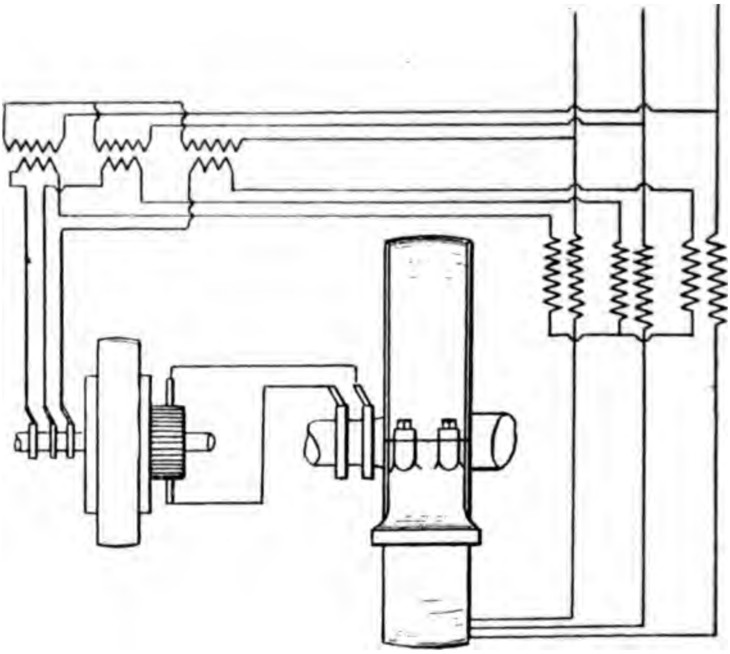

FIG. 224.

The battery is also used for lighting the station, so that in the event of a complete breakdown of running machinery in the evenings, light will be available for seeing to repairs.

Much attention has been paid to the compounding of alternators, and one or two methods have been fairly successful. In one, the exciter takes the form of a rotary converter, and receives alternating current from two sets of transformers, the primary winding of one set being connected as a shunt to the main generator, the primary of the other being in the main circuit. The secondary winding of these two sets of transformers are in series, and connected to the slip rings of the exciter converter, which thus has an alternating electromotive force supplied to it, increasing in proportion to the load. Direct current is then taken from the commutator of the converter to the field winding of the main generator.

At no load the applied alternating electromotive force is that due to the shunt transformers alone, and the direct electromotive force, bearing a fixed ratio to the alternating, will be that required to give the no-load exciting current. At full load the impressed alternating electromotive force rises, and with it the direct electromotive force and the exciting current. In the same way a certain amount of over-compounding can be obtained. A diagram of the connections of this arrangement is shown in Fig. 224.

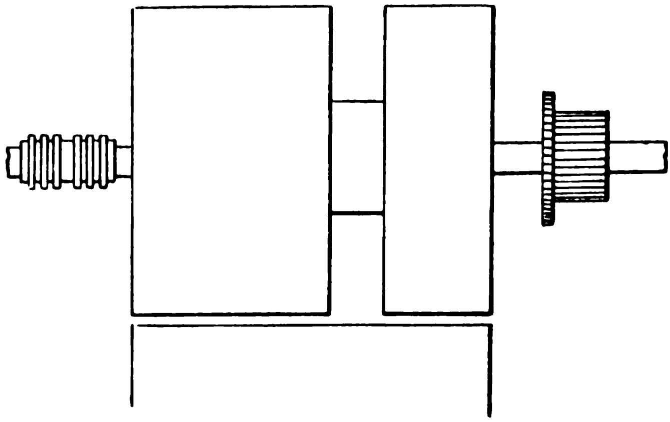

FIG. 225.

A special exciter for obtaining the same result, designed by M. Leblanc, is shown diagrammatically in Fig. 225. In this, three independent windings wound on two separate armature cores, fixed to the same shaft, revolve between a system of field poles. One winding, embracing *both* armature cores, is connected to a commutator as in an ordinary direct-current machine. Two other windings, one on each core, are connected to two sets of slip rings, one in series with the armature circuit of the main alternator, and the other as a shunt across its terminals. The

[redacted]

machine runs as a synchronous motor from the alternating shunt-circuit winding, direct current being taken to the main-field winding from the commutator. Any increase in the current taken from the main alternator by passing round the exciter armature tends to increase its field, which is further strengthened by any increase in the angle of lag in its circuit. Thus the exciting current is automatically raised or lowered to suit the nature of the load, and we get an exciter which maintains an approximately constant terminal potential difference for all loads.

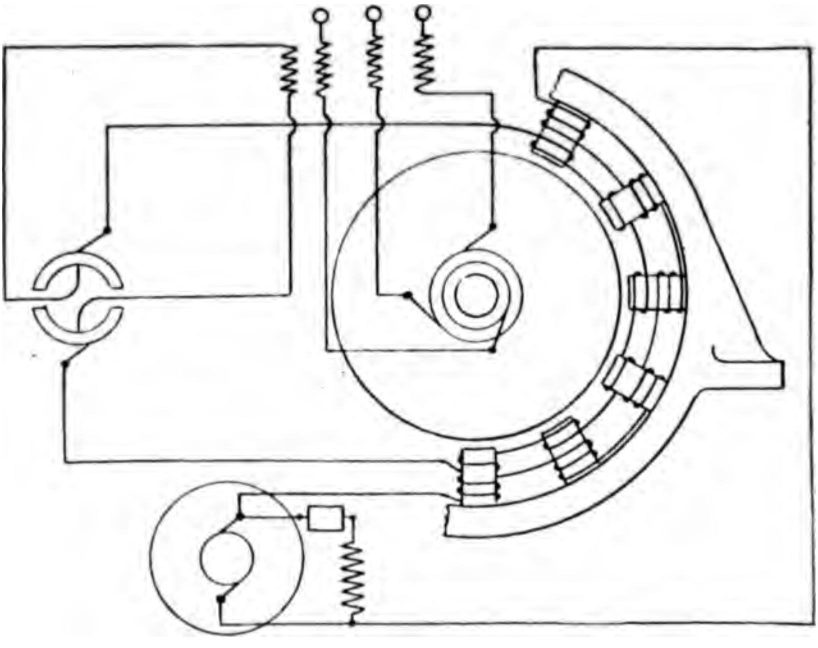

FIG. 226.

Several arrangements have been used in which a separate and independent compound winding is fed by rectified currents, *i.e.* alternating current, obtained from the secondary of a transformer, whose primary is in the main circuit, which is changed to direct current by a commutator rotating in synchronism with the alternating current. The current in the compound winding is thus

[redacted]

proportional to the load current. The connections for this are shown diagrammatically in Fig. 226.

Mr. Miles Walker has devised an arrangement of field-pole pieces which, with constant field excitation, gives a certain amount of compounding or over-compounding, due to armature reaction only. This is, of course, practically instantaneous in its action, whereas in some of the arrangements employed, time is required for the field to build itself up to meet the altered conditions, often taking as much as three or four seconds. Mr. Walker's method apparently compounds excellently in all cases where the power factor is above, say, 0·85, and for power factors of 0·9 or 0·95, over-compounding can be obtained. With power factors less than 0·85 the arrangement fails, for we get the reverse action, and the pressure drops considerably more with than without the auxiliary poles. Fig. 227 shows the arrangement of the field poles. The main pole is surrounded by an exciting coil, which normally gives a high degree of saturation to it, the flux of which is therefore not easily disturbed by armature reaction. The smaller pole is either unwound, or is wound with a secondary coil embracing the whole as shown, so as to vary the normal voltage of the machine. In either case the smaller pole is either unmagnetized at no load, or is considerably undersaturated, and ready to respond to the armature magnemotive force. The dotted curve in the same figure shows by its depth below or above the line representing the armature face, the direction and magnitude of the cross flux due to armature reaction with a power factor of unity. This wave of flux rotates in phase with the main field, and therefore occupies

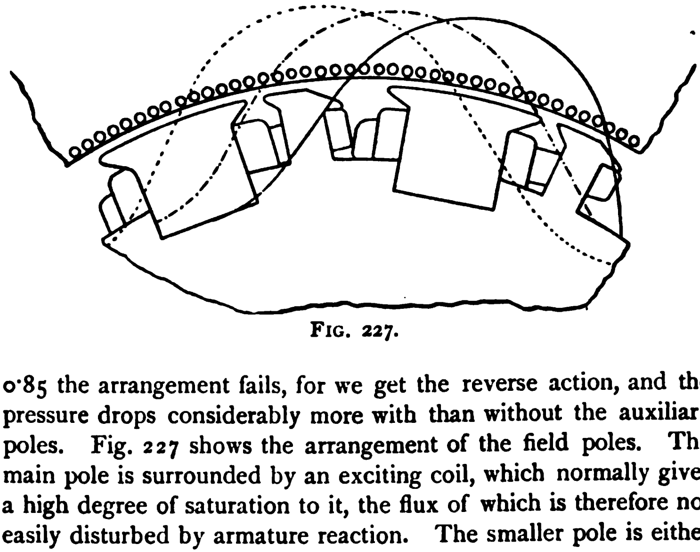

FIG. 227.

always the same position relatively to the poles. It will be seen that on the whole it has no effect on the main pole, magnetizing and demagnetizing to an equal degree. It, however, has a strong magnetizing action on the auxiliary pole, which, owing to its unsaturated and highly permeable condition, allows a large flux to cross, and so raise the electromotive force.

The second chain-dotted curve shows a certain small angle of lag in the armature current, and now the cross field tends to weaken the main pole, though still strengthening the auxiliary pole, but to a less degree; the demagnetizing effect on the main pole, however, is not appreciable, owing to its being highly saturated by the main-field excitation, and we therefore still get a certain amount of compounding. When the power factor has fallen so low that the rotating wave of armature cross flux lags behind, as shown in the full line, there is a demagnetizing effect on the main pole, and a reversed magnetization of the auxiliary pole which now lowers the electromotive force. In many instances, however, the power factor seldom or never falls below 0·85, in which case this method of compounding the machine is serviceable.

Mr. A. Heyland has devised a self-exciting and compounding arrangement which works admirably in practice. It, however, necessitates the addition of a commutator, but the number of segments being small, they can be made fairly massive, and sparking being entirely absent, no trouble is experienced in its employment. The arrangement compensates not only for changing load, but for changing power factor also. This will best be understood from Mr. Heyland's own diagram (Fig. 228), representing the case of a two-pole generator or a multipolar machine with the commutator driven at p times the speed of the generator, p being the number of pairs of poles.

In this example the commutator consists of eighteen segments, the width of the brushes being such as to span slightly more than three segments. The field-magnet winding is divided up into six circuits in parallel, which are interconnected by resistances at both ends. If the number of field poles is not a multiple of six, two or more windings are put on each pole, so as to produce six equal resistance circuits.

The windings are connected to the commutator segments, as shown in the figure, where r, r, r represent the windings, and p, p, p the interconnecting resistances. Three-phase current is fed into

[redacted]

the commutator by the brushes I., II., and III., which supply the normal exciting current from the secondary windings of a three-phase transformer, joined up in mesh connection; the primaries being connected direct to the terminals of the generator. Consider the time when the current, entering by brush I., has attained its maximum value. The currents in the other brushes will have half their maximum values in the reverse direction, and the brushes being in the position shown, the current will divide among the windings in practically equal proportion. At one-third revolution later brush II. will have its maximum current, and the commutator having moved round an equal amount, the same segments will be facing this brush, and will therefore receive current in the same direction as before. This is repeated at brush III., so that as each brush receives its maximum current it also receives the proper commutator bars to feed into, so as to maintain a unidirectional current in the field winding. In all intermediate positions the current divides more or less equally through the coils, for, owing to their large self-induction, and to their being interconnected by the small resistances, the variations that occur are small and very rapid. The fact of there being always several circuits through which the current may pass prevents any chance of sparking at the commutator.

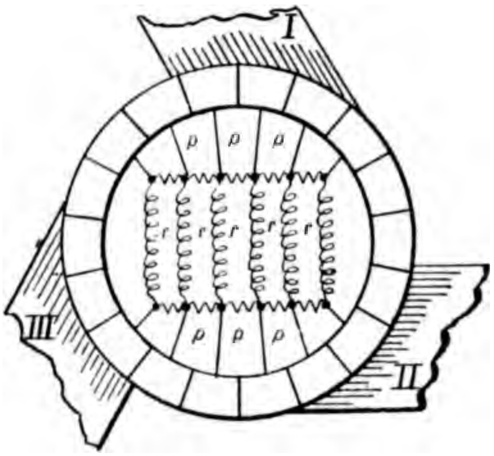

FIG. 228.

[redacted]

To compound the machine, a second three-phase transformer, whose primary winding is connected in series with the terminals of the main generator, has its secondary windings star-connected and joined to the same three brushes, and therefore additional current is fed into the commutator proportional to the load and to the power factor also. With the two transformers connected in a similar manner, two sets of brushes would be required spaced 90° apart, so as to supply current proportional to the wattless component which lags by 90°, but there being a phase difference of 30° between star and mesh connection, the angle between the two sets of brushes is increased from 90° to 120°, which brings the two into line and allows of one set for both transformers. The connections of the two transformers are shown in Fig. 229.

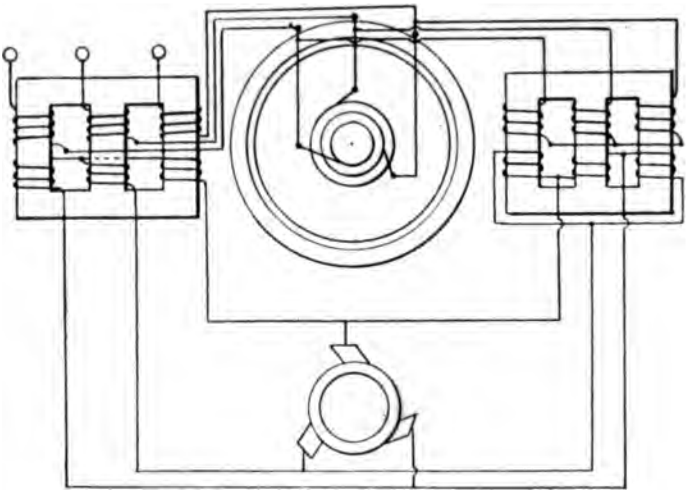

FIG. 229.

When alternators are to be run in parallel we have to see that they are alike, not only in electromotive force, but also in frequency and in phase, before switching in. Two voltmeters will tell us when the electromotive forces are alike, but we require some special indicator, visible to the engine-driver as well as to the switch-board attendant, to indicate when the two are alike in frequency and phase. Such indicators are known as "synchronizers" or "synchroscopes," and the operation of getting a machine exactly similar in phase and voltage to one or more already running, is known as synchronizing.

It will be seen how important it is that the two machines should be alike in phase as well as electromotive force before connecting them together, for the voltmeter indicates the effective value of the latter, and this may be exactly the same in the two cases, though differing in phase by 180°. In such a case the two machines would be in series with double the normal electromotive force in their circuit, and if switched in, an exceedingly large current would surge round, possibly breaking down both machines.

The synchronizers employed vary somewhat. For low-voltage machines all that is necessary is a lamp, whose normal voltage is

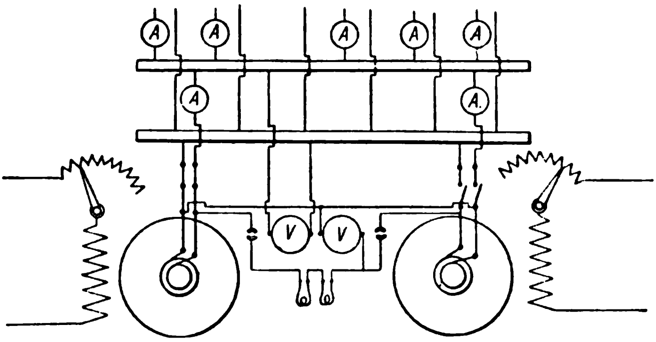

FIG. 230.

equal to that of the two machines added, or a couple of lamps in series, connected with the two machines in such a manner that when the two are in phase the lamps light up, and when out of phase dim down, and finally go out. The rate at which the lamps light up will indicate to the engine-driver when the speed is nearly correct, and the point of maximum brightness indicates when the two are exactly in phase. Such an arrangement is shown diagrammatically in Fig. 230.

The operation of synchronizing and switching in is as follows. The machine is first run up to speed and excited so as to give the same electromotive force as the one or more already running. The synchronizing lamps are now plugged in, when they will probably be flickering more or less rapidly. The speed is then adjusted until the lamps are pulsating slowly, as the machines come slowly into phase and fall out again. The main switch is closed when the lamps are slowly increasing in illumination, and have almost attained their maximum brightness. It is best to switch in just *before* rather than after the point of maximum brightness, for there is a certain amount of lag in the glowing of the filament.

With high-voltage machines a transformer is usually employed to reduce the pressure to that suitable for the lamp or lamps. One form of this arrangement is shown diagrammatically in Fig. 231. Here one limb of the transformer is connected to the bus-bars, while the other is connected to the incoming machine. The middle limb is wound so as to produce an electromotive force equal to that of the lamp connected to it, when the double flux due to the coils on the two side limbs interlink with it. These two coils are connected in such a way that when in phase they develop a flux in the same direction, and therefore in opposition so far as their own circuits are concerned, but in parallel through the centre coil. When out of phase the fields due to the two side coils are in series, and consequently, there being no flux in the centre coil, the lamp ceases to glow.

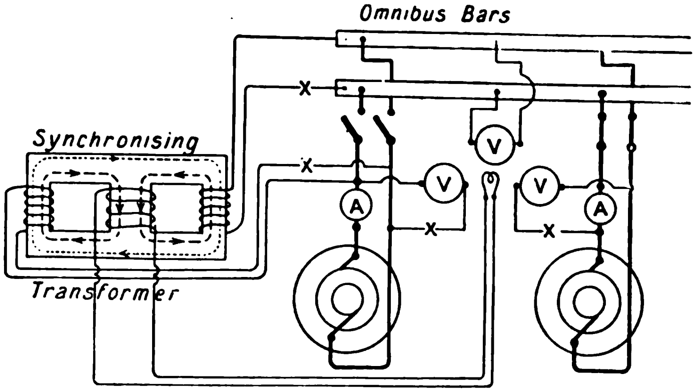

FIG. 231.

Messrs. Everett-Edgcumbe make a rotary synchronizer, which has come into fairly extended use. It consists of a small induction motor, the stator being fixed in a case, the rotor being furnished with a pointer moving over a dial. A rotating magnetic field is produced in both by winding a double circuit on each, with a lamp (non-inductive resistance) in one and a choking coil in the other circuit. The two circuits being in parallel, there is a phase difference between the currents in them which gives rise to more or less rotation of the flux. The stator is excited from the busbars, and the rotor from the incoming machine. If the two are in phase, the two fields will revolve at equal rate, and the rotor will remain stationary; but if one field be revolving faster than the other, the rotor will revolve in one direction or the other with a speed equal to the difference in speed of the two, so as to keep the fields in step. The speed of the pointer therefore indicates the difference in speed of the two machines, while the direction of its rotation shows whether the incoming machine is running too fast or too slow. The instrument is also provided with a visual signal, consisting of a rocking lever of aluminium actuated by the rotor, which carries a red or green screen in front of an incandescent lamp, depending on its direction of rotation. The engine-driver knows by the red light being visible that the machine is running too fast, while the green light indicates too slow running.

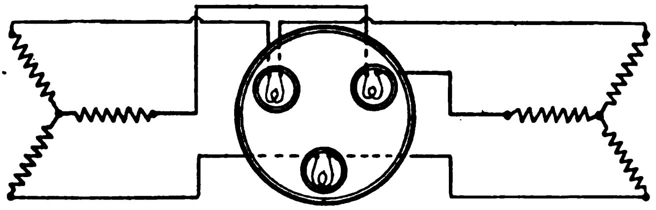

FIG. 232.

Polyphase machines are often synchronized on one phase only, in a similar manner to single-phase machines, though in certain cases special synchronizers are employed. One of the most common devices for three-phase machines consists of three lamps arranged in a case behind holes cut in a metal screen, so as to occupy the corners of an equilateral triangle. These lamps form the connection between the secondary windings of two sets of three-phase transformers, one operated by the incoming machine, and the other by the machine already running, as shown in Fig. 232.

If now the two machines are exactly alike in phase, there will be no potential difference on the ends of the lamps, and

[redacted]

consequently they will remain dark. The moment they fall out of step, however, due to changing speed, a potential difference will exist between the various lamp connections, and they will brighten up alternately with a frequency proportional to the difference in speed, one having its maximum brightness when the other two are dull red. The order in which they brighten up indicates whether the incoming machine is running too fast or too slow. Usually when the light appears to travel round in a clockwise direction, the speed of the incoming machine is too high.

Many inventors have been engaged in efforts to make synchronizing entirely automatic, with more or less success. Ironless-cored machines, having very little inductance in themselves, are often protected by inserting an inductance into the circuit of the incoming machine, which can be cut out or short-circuited after synchronizing.

One of the effects of bad synchronizing is the racking action produced on the armature coils, especially the end connections, which should therefore be very securely fixed.

To run well in parallel, alternators should be alike in their characteristics and wave shape; differences in size does not matter, for each machine can be made to take its fair share of the load by adjusting its excitation. If the two machines generate different wave shapes, however, there will be periods of different electromotive force at each cycle, which will lead to large surging currents between the two machines of a higher frequency than that of the main current. This will be seen by considering the curves (Fig. 233), where one machine is developing a flat-topped curve, while the other is more or less peaked, giving rise to a resultant electromotive force of three times the frequency. These surging currents lead to a loss of energy, and lower the capacity of both machines by the additional heating so produced.

Unless the governing of engines driving alternators in parallel be very good, and the turning moment throughout the revolution quite regular, there will be frequent times when one machine will tend to lag behind the other. It cannot do so, however; for the slightest amount of lag means a difference in phase between them, and consequently a large current will surge round the lagging machine to pull it along. Where this effect happens, it tends to increase, for receiving a large motoring current in this way, it is often pulled round so as to become the leading machine, which

[redacted]

then in turn supplies a motoring current to the first, for the large motoring current which helped the lagging machine forward tended to slow down the leading machine by putting an extra load on it. It is not uncommon to find machines surging in this way to quite a large extent. In fact, cases are known where machines have been so addicted to this as to make it almost impossible to run them in parallel. This is especially the case with small gas-engine plants, and, in fact, in any case where the engine governing is not of the most perfect design.

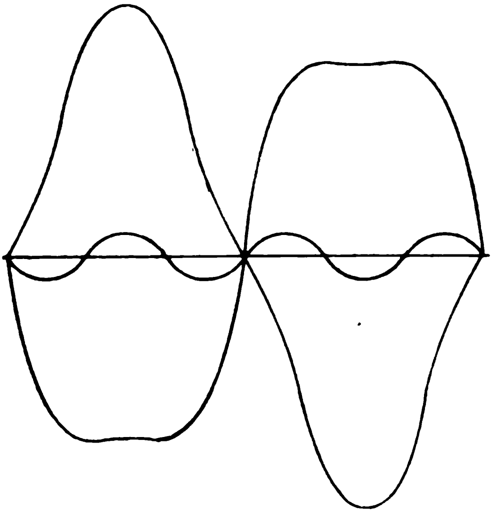

FIG. 233.

This surging, or *hunting*, as it is sometimes called, is minimized, and in many cases prevented entirely by providing the field-magnet system with "damping" coils, or "amortisseur" coils. The former often take the form of thick copper plates, placed across the pole horns as close to the armature as possible. These are often cast so as to slide between adjacent pole tips, and are formed with holes so as not to interfere with the ventilation of the field coils and armature. Amortisseur coils are formed by embedding thick rods of copper in the pole shoes; stout copper rings passing round the outside of the latter to which the copper rods are connected at both ends. These are more effective than

[redacted]

the former, when sufficient copper is employed, but are usually more expensive; the weight of copper required, to make them really effective, being approximately equal to that in the armature winding.

The action of damping coils or amortisseur coils is probably as follows: The lagging machine first receives a motoring current to pull it into step, which reacts on the main field and draws it to the advancing pole tip. This magnetic distortion gives an impulse to the rotor, which, owing to its inertia, overshoots the mark and causes it to deliver a motoring current to the other machine. This current now distorts the main field in the opposite direction, for it is a generator current, and therefore the flux is swept to the receding pole tip, which tends to draw it back. This swinging of the field across the face of the pole, first to one tip and then to the other, cuts through the damping or amortisseur coils, and induces in them large currents in such a direction as tends to oppose the swinging of the field, and they therefore prevent any accumulative effects.

We saw, in Chapter VI., that a capacity in parallel with an inductive circuit may be so adjusted as to provide the wattless component, and so raise the power factor. This is sometimes taken advantage of in stations where the power factor is apt to fall considerably. An alternator, single or polyphase, when synchronized and switched in parallel with others, will run as motor, and if it be then over-excited, it acts as a condenser, giving rise to an angle of lead, and supplying the wattless component, thus raising the power factor of the main alternators to unity. For this purpose an extra small machine is often installed, with arrangements for running it up to synchronous speed.

INDEX

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